TMDL DEVELOPMENT FOR PHOSPHORUS LOADING IN THE LOWER CATAWBA RIVER WATERSHED

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ABSTRACT

The primary goal of this study was to provide a detailed quantitative analysis of data and model simulations to support development of an effective TMDL for phosphorus in the lower Catawba River basin of South Carolina. The major objectives were to (1) develop, calibrate and verify a process-based, watershed/water quality model of the lower Catawba River basin, (2) use the model to quantify implications of point and nonpoint sources of phosphorus loading related to key management scenarios for wastewater regulation and nonpoint source runoff control, and to (3) establish quantitative guidelines for an effective TMDL for phosphorus in the basin.

Through a subcontract with Systech Engineering, we obtained an updated version of the WARMF model (Watershed Analysis Risk Management Framework), which included a preliminary calibration for the Lower Catawba system. After final calibrations (conducted by USC), the model simulated an average loading of total phosphorus to the major reservoirs of the Lower Catawba of 2,097 kg/day during the simulated baseline period between 1996 and 1998. This loading was composed largely of point source discharges (46%) and nonpoint sources of runoff (39%) with the remaining 15% from upstream sources to the Lower Catawba (outflow from Lake Wylie). A series of management scenarios was then simulated to predict the effects of reductions in point sources (including recent permit reductions for NC and SC, plus an additional 50% reduction in SC point sources) and nonpoint sources (including a 2/3 reduction in fertilizer applications as well as a 10 m vegetated buffer along 90 % of all streams in the basin). The cumulative effect of these scenarios would reduce total phosphorus loading by 40% and would reduce exceedences of the chlorophyll standard in the major reservoirs to < 25%. Although these scenarios would reduce the phosphorus concentrations in the reservoirs, the annual variability would still yield > 25% exceedence of the phosphorus standard. To limit phosphorus exceedences to < 25% would require reducing the total load to < 600 kg/day (representing a 70% reduction from base conditions) and would require additional limits on both point and nonpoint sources.

INTRODUCTION

Excessive nutrient loading and eutrophication of aquatic ecosystems have been recognized worldwide as major causes of water quality impairment for the past 30 years (Edmondson 1969, Vollenweider 1976, Cooke *et al.* 1993). Elevated concentrations of nutrients such as phosphorus and nitrogen often lead to water quality problems related to excessive algal blooms, elevated pH levels, accumulation of organic matter, and subsequent depletion of dissolved oxygen. There has been some historical success in reversing the detrimental effects of eutrophication, especially in cases where wastewater discharges can be diverted (Edmondson 1981). However, complex issues of nutrient loading and eutrophication remain as major topics in aquatic ecology and water quality management (Dodds 2002, Kalff 2002).

A recent EPA summary of water quality trends in the United States cited “nutrients” as the leading cause of water quality problems in lakes and reservoirs (US EPA 2000). In South Carolina, 12 lakes (26 sampling stations) were included on the state’s list of impaired waters because of frequent exceedences of state water quality standards for phosphorus, pH, and algal biomass (SC DHEC 2002). As required by the US EPA, states must develop management targets for pollutant loads to water bodies that exhibit significant exceedences of state water quality standards (USEPA 1991). This "total maximum daily load" (TMDL) should represent the maximum input (kg da^{-1} or lb da^{-1}) from point source discharges and nonpoint sources of runoff that a water body can receive and still meet water quality standards (USEPA 1991). The primary goal of this study was to provide a detailed quantitative analysis of monitoring data and model simulations to support development of an effective TMDL for phosphorus in the lower Catawba River basin one of the major watersheds in SC that has been targeted for remediation of excessive phosphorus concentrations.

Study Area. The lower Catawba River basin is defined here as the drainage basin of the Catawba River between the outflow of Lake Wylie (on the NC/SC border) and the outflow of Lake Wateree (Fig. 1). The watershed is largely forested (69.4%, Table 1) although sub-basins include areas of significant agricultural land use (up to 29 % in the 12-Mile Creek sub-basin) and urban/industrial development (up to 41 % in the Sugar Creek sub-basin, which drains portions of metropolitan Charlotte, NC). The 2 major reservoirs on the lower Catawba River (Fishing Creek Reservoir and Lake Wateree) have both exhibited sustained exceedences of the 0.06 mg/L phosphorus standard for piedmont reservoirs (Fig. 2). In addition, the largest and most downstream reservoir (Lake Wateree) has also exhibited frequent exceedences of the 40 µg/L chlorophyll-a standard in the upper embayments and middle regions of the reservoir (Fig.2). These 2 reservoirs represent the priority water bodies targeted for reductions in phosphorus loading in the watershed.

A partial phosphorus budget for this basin can be viewed as the difference in phosphorus mass transport between the upstream outflow from Lake Wylie and the downstream inflow to Lake Wateree (Fig. 3). The 5-6-fold increase in phosphorus load can be attributed to phosphorus loads from a combination of nonpoint sources of runoff and point sources of wastewater discharge from industry and municipalities (Table 2). While the sum of the major point sources amounts to almost 90% of the 2576 lb/d difference between these loading rates (Fig. 4), this partial budget does not account for other sources and sinks of phosphorus due to biogeochemical processes within the basin (uptake, recycle, sedimentation etc). An effective TMDL for the system should be based on a rigorous functional understanding of the complex hydrodynamics, ecological functions, and physio-chemical reactions that govern the relationships between pollutant load and water quality patterns in the aquatic ecosystem (Effler et al. 2002). Understanding these interactions often requires use of computerized simulation models that integrate physical and biological interactions over a range of temporal and spatial scales of variation. Such models require careful calibration and verification with available data and a thorough analysis of model predictions over a range of relevant conditions. The major objectives of this study were to

- Calibrate and verify a process-based, watershed/water quality model of the lower Catawba River basin,
- Use the model to quantify implications of point and nonpoint sources of phosphorus loading related to key management scenarios for wastewater regulation and nonpoint source runoff control, and
- Establish quantitative guidelines for an effective TMDL for phosphorus in the basin.

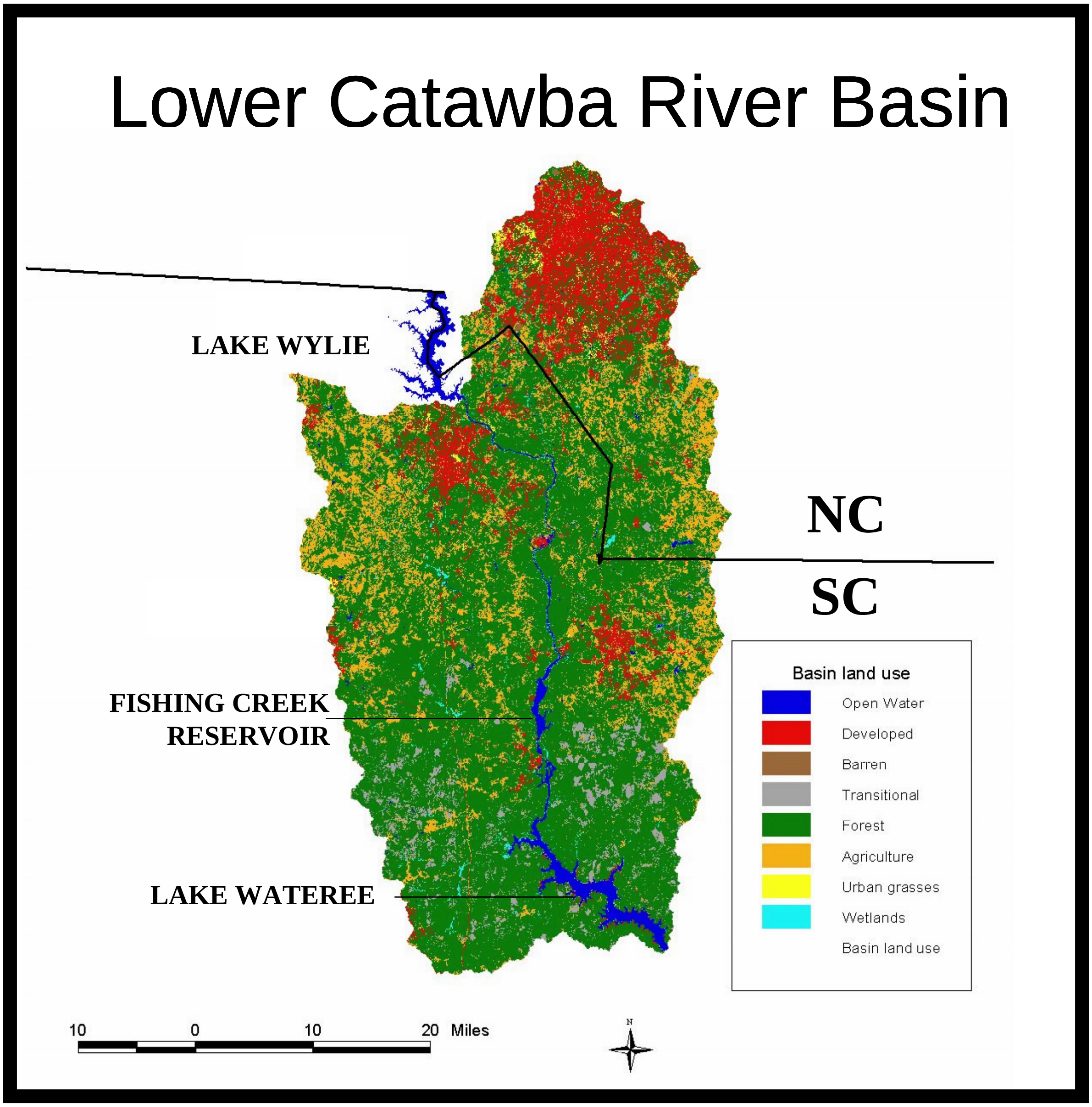


Fig. 1. Map of the lower Catawba River basin. Land use categories are based on Multi-Resolution Land Characteristics (MRLC) Consortium Land Cover Maps obtained from USEPA (http://www.epa.gov/mrlc/). The classifications are based on imagery acquired in 1993-95.

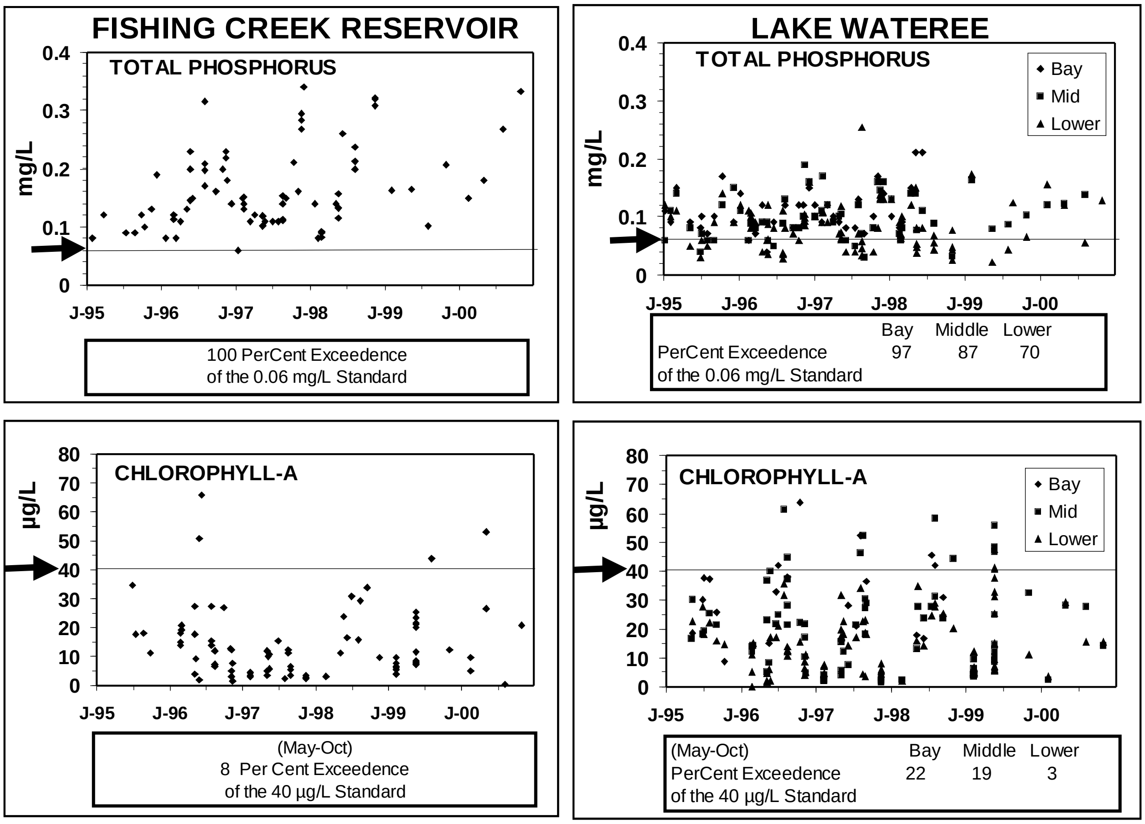


Fig. 2. Total phosphorus and chlorophyll-a monitoring data from Fishing Creek Reservoir and Lake Wateree (1995-2000). The horizontal lines on each panel represent the South Carolina water quality standards for total phosphorus (0.06 mg/L) and chlorophyll-a (40 µg/L) in piedmont lakes and reservoirs. Data for Fishing Creek Reservoir were from SCDHEC station CW-057 and DUKE WQ Station 175. Data for Lake Wateree were from SCDHEC CW-208 (Dutchman's Creek Embayment), and SCDHEC CW-207 and DUKE WQ 130 (Middle) and SCDHEC 209 and DUKE WQ 105 (Lower). These monitoring data were assembled by Systech Engineering from the EPA STORET database and incorporated in the database for their "Watershed Analysis Risk Management Framework" model (WARMF 5.20). Details of the model will be discussed in a later section.

Table 1. Land Use/Land Cover for the Lower Catawba Basin (from the outflow of Lake Wylie to the outflow of Lake Wateree) Data from SCDHEC (2003) and NC DENR (1999)

Hydrologic Units	USGS HUC [1]	Total Area (km^2)	LAND USE/LAND COVER % Forest	%Urban	%Water	%Agr	%Scrub	%Barren
Catawba River	03050103- 010	426	68.7	11.3	7.6	6.7	5.1	0.6
Sugar Creek	03050103- 020[2]	551	42.8	41.0	0.6	14.1	0.8	0.8
12-Mile Creek	03050103- 030a[2,3]	377	65.2	4.2	0.5	29.1	0.5	0.5
Waxhaw Creek	03050103- 030b[2,3]	128	75.6	1.3	0.3	21.3	0.7	0.8
Cane Creek	03050103- 040[2]	406	62.0	8.8	0.9	26.7	0.7	0.8
Upper Fishing Creek	03050103- 050	129	52.0	5.9	0.8	24.4	15.1	1.7
Lower Fishing Creek	03050103- 060	551	61.0	6.1	0.5	17.6	13.4	1.4
Tinker Creek	03050103- 070	69	77.5	0.4	0.7	11.3	10.0	0.1
Camp Creek	03050103- 080	107	88.7	0.0	0.1	7.6	3.0	0.6
Rocky Creek	03050103- 090	518	79.8	1.7	0.4	10.0	7.9	0.2
Lake Wateree	03050104- 010	845	87.2	0.7	6.3	2.2	3.5	0.1
Big Wateree Creek	03050104- 020	152	87.4	0.8	0.5	6.6	4.5	0.2
	Overall Total	4257	69.4	9.0	2.4	13.5	5.0	0.6

[1] US Geological Survey Hydrologic Unit Codes

[2] includes NC and SC portions of the sub-basin

[3] the USGS HUC combines 12-Mile and Waxhaw Creeks; in this table, the 2 sub-basins are separated as -030a and -030b

Table 2. Major point sources of phosphorus for the Lower Catawba. Data assembled from the WARMF model[1] (Ver. 5.2) database derived from monthly discharge monitoring reports submitted to SC DHEC, NC DENR, or EPA Permit Compliance System. Unless noted otherwise, these values represent means and standard deviations (SD) of data collected between 1995 and 2000. Charts of detailed monthly values are provided in Appendix D.

			Discharge Monitoring Reports					
		Permitted Discharge	Discharge Volume (MGD)[2]		Phosphorus Conc.(mg/L)		Phosphorus Load (lb/day)	
NPDES #	Name	MGD[2]	Mean	± SD	Mean	± SD	Mean	± SD
MAJOR INDUSTRIAL SOURCES								
SC0001783	Hoechst-Celanse(#1); chemical [3]	M/R[4]	2.9	0.4	5.2	4.0	122.4	90.7
SC0001015	Bowater Inc.; pulp and paper	M/R[4]	31.1	13.3	1.1	0.9	267.5	248.2
SC0003255	Springs Ind/Grace; textile	M/R[4]	5.5	0.7	0.2	0.01	9.2	1.1
MAJOR MUNICIPAL SOURCES								
NC0024970	CMU[5]-McAlpine Creek	64.0	38.1	5.2	2.9	1.0	906.7	322.4
NC0024937	CMU[5]-Sugar Creek	20.0	12.9	2.4	6.2	2.2	665.3	233.2
NC0024945	CMU[5]-Irwin Creek	15.0	8.8	1.8	1.8	0.8	131.1	70.4
SC0020371	Fort Mill	2.0	0.9	0.2	1.8	0.9	13.8	8.1
SC0020443	Rock Hill/Manchester Crk	20.0	8.6	1.3	2.0	0.7	140.3	41.3
SC0046892	Lancaster/Catawba	5.8	2.6	0.5	1.6	0.9	31.7	16.0
SC0038156	City of York/Fishing Crk [6]	2.0	0.9	0.1	0.7	0.3	5.4	2.5
			total point source load=				2293.4	

[1] The WARMF model (Watershed Analysis: Risk Management Framework, Chen et al. 1995, 1996, 1997) was used for model analyses in this report (discussed later).

[2] Million gallons per day

[3] Data based on special study in 1999

[4] Volume discharge not specified in permit; M/R indicates " monitor and report"

[5] Charlotte-Mecklenburg Utilities (North Carolina)

[6] Data from year 2000

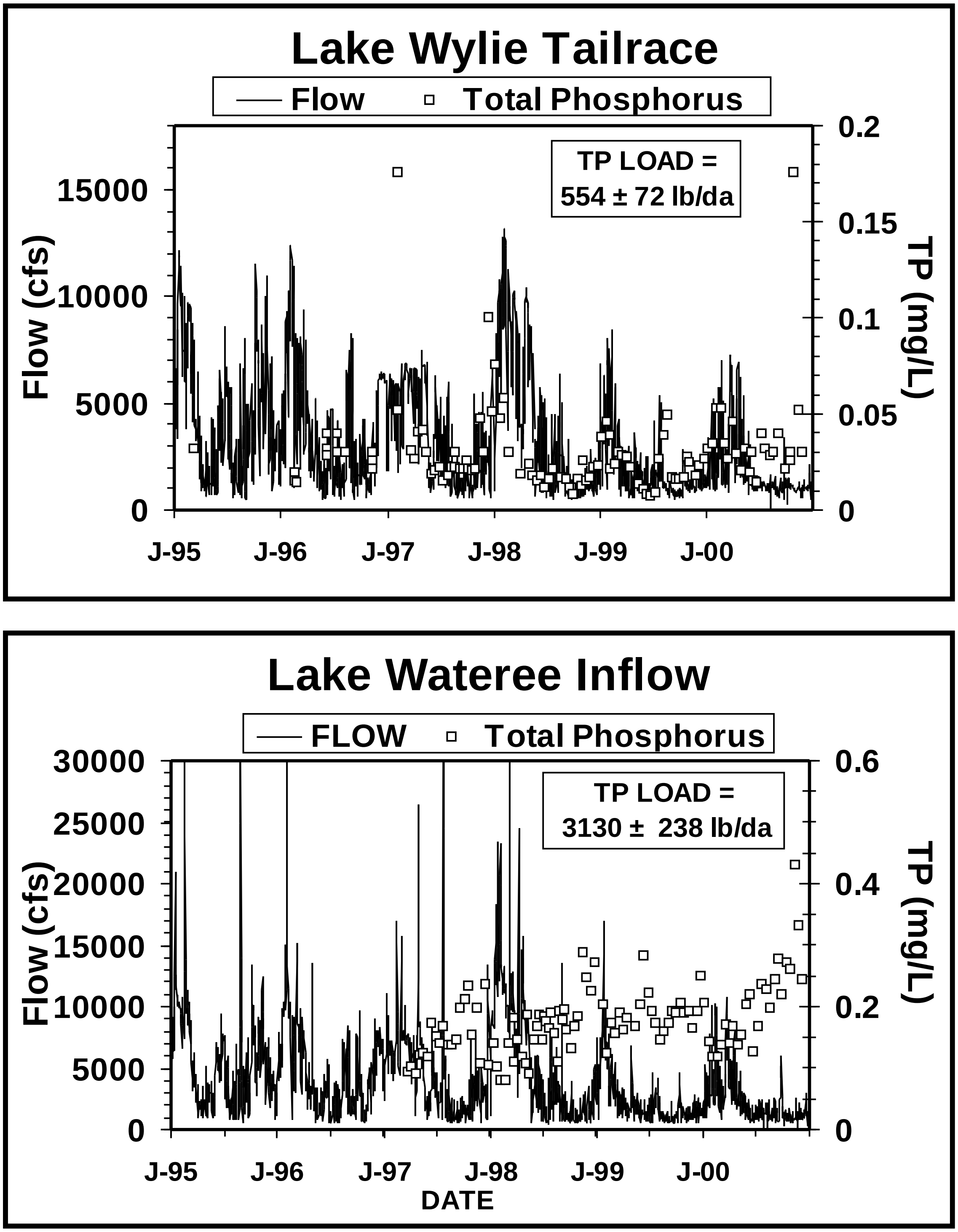


Fig. 3. Stream discharge and total phosphorus concentrations in Lake Wylie outflow (Duke station at Wylie tailrace) and Lake Wateree inflow. The inflow to Lake Wateree is taken as the outflow from the small reservoir (Cedar Creek) 4 km upstream (Duke station at Cedar Creek tailrace). Data are plotted from the WARMF database.

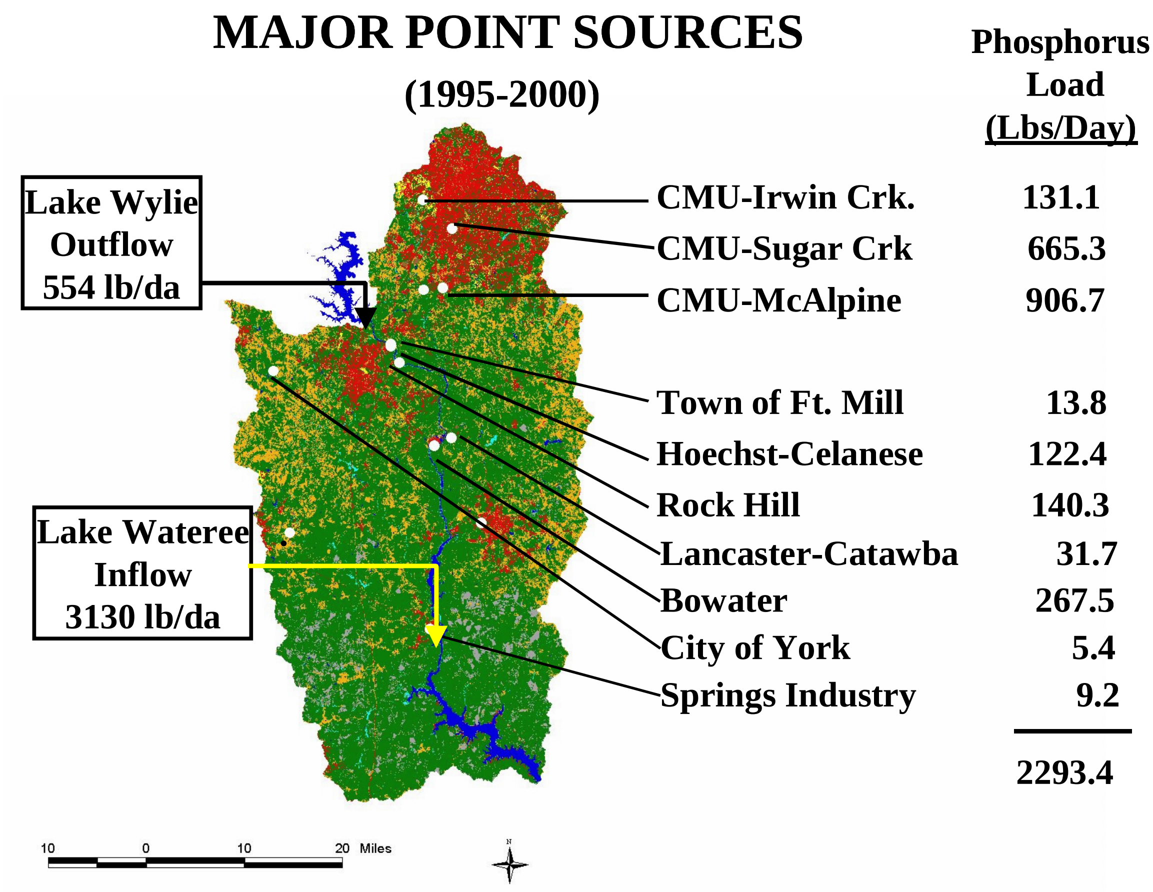


Fig. 4. Location and summation of major point sources of phosphorus along the lower Catawba River.

METHODOLOGY

The WARMF Model

A major component of this study was the enhanced development and preliminary calibration, of a state-of-the-art watershed simulation model (WARMF, Watershed Analysis Risk Management Framework) under contract to Systech Engineering (Chen *et al.* 1995, 1996, 1997). The core component of WARMF is a physically based, dynamic simulation model which combines information on land use, soils, and meteorology to simulate runoff and nonpoint source loads from a network of catchments (Fig. 5). The model further combines these results with information on point source discharges and reservoir release rates to route water through the basin and to simulate water quality dynamics in the streams and lakes. The water quality dynamics within the stream reaches and lake segments are simulated as interactions among sediments, nutrients, oxygen, and biota; model functions are similar to those established in other

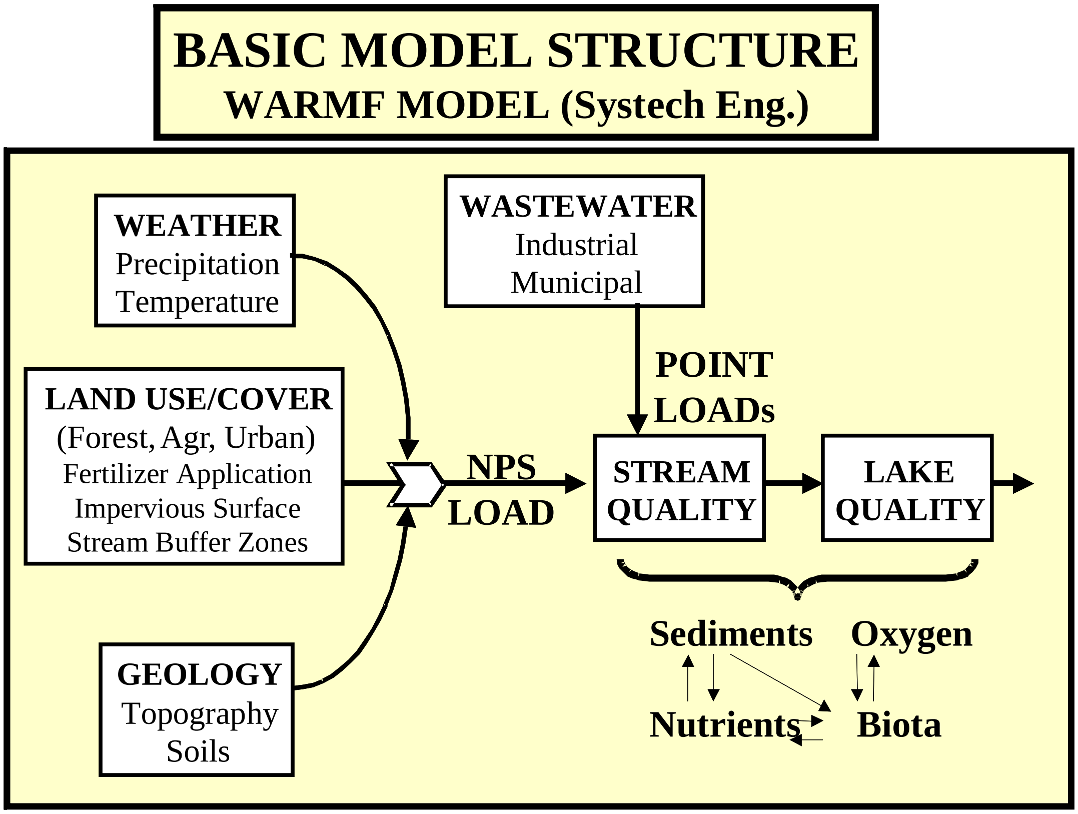


Fig. 5. The basic structure of the WARMF model.

EPA-supported modeling packages (Brown and Barnwell 1987, Ambrose, et al. 1993). Watershed/water quality analysis can range from headwater stream segments to regional basins. Sub-basin aggregation (or disaggregation) needed for specific model applications can be handled within the model framework.

Systech's main tasks in the sub-contract were to (1) develop the necessary code to segment the major lakes into upper, middle, and lower regions, (2) to compile relevant input data (meteorology, land use, geology, point source discharges) and monitoring data, and (3) accomplish a preliminary calibration of model parameters for the lower Catawba River system. USC conducted the final calibration and verification of the model. Once calibrated and verified, the model was used to test the sensitivity of various combinations of land use pattern and waste load allocation on simulated water quality trends for the basin.

Monitoring Data and Time Frame

We executed the WARMF model to simulate the interval from September 1, 1995 through December 31, 2000. For calibration we used the three-year interval from January 1, 1996 through December 31, 1998. This interval was selected because it had the greatest density of observed data points, thus allowing statistical comparison of simulated and observed values. Observed values were obtained by Systech from sampling results by SCDHEC and Duke Energy.

As an aid for Systech in their model calibration, we collected additional discharge and water quality data from the upper Fishing Creek watershed. Details of the site, sampling network, protocols, and results are provided in Appendix A.

Calibration

Calibration focused on hydrology, nutrients, and chlorophyll-a (CHLa). Reservoir nutrient calibration for total phosphorus (TOTP) and total nitrogen (TOTN) concentrations focused on Fishing Creek Reservoir and Lake Wateree segments 2, 3, and 5 (Fig 6). Calibration for CHLa concentrations occurred only in Lake Wateree segments 2, 3, and 5. Fishing Creek Reservoir (for CHLa) and other reservoir segments (for CHLa, TOTP, and TOTN) were not included due to lack or absence of observed values. (Further use of CHLa, TOTP, and TOTN will refer to concentrations unless otherwise stated.)

Systech calibrated the model for river and reservoir hydrology. They also began nutrient calibration by ensuring point source (PS) loading included the most current values, implementing stream riparian buffers based on the results of a study by Duke Energy, and adjusting other nonpoint source (NPS) loading parameters within frequently accepted ranges (see Appendix B for copies of model calibration and other technical documentation from Systech). Our calibration of nutrients in the reservoirs required further adjustments to NPS parameters in the watershed so we reconfirmed their calibration in the Catawba River segments upstream from Fishing Creek Reservoir (Fig. 6).

Calibration status was assessed as goodness-of-fit of the quarterly means of the observed and simulated values. We used two metrics, the root mean squared error (RMSE) and the Kolmogorov-Smirnov (KS) two-sample test. The RMSE (Helsel and Hirsch, 1992) is a summary statistic indicating the magnitude of the difference between observed and simulated values. Low values of the RMSE indicate a better fit than high values. The statistic is in the units of the base parameter so model fit is assessed relative to the range of data used to derive the value. The KS test (Conover, 1999; Reckhow et al., 1990) is a nonparametric test of the null hypothesis that the observed and simulated means come from the same empirical distribution function (good fit). Thus p-values larger than a stated α-level (such as 0.05 or 0.10) indicate a good fit. The KS test is particularly suited for tests with small sample sizes (McCuen, 2002). To assess hydrology calibration we used the Pearson correlation in addition to the RMSE and KS tests.

Simulation results were modified by adjusting certain NPS loading parameters (for TOTP and TOTN) and phytoplankton growth parameters (for CHLa). The WARMF model does not perform the statistical tests we used so after each simulation run the required data were extracted from WARMF (using a feature in WARMF) and imported into Microsoft Excel and SAS (SAS, 1988) for analysis and graphical presentation.

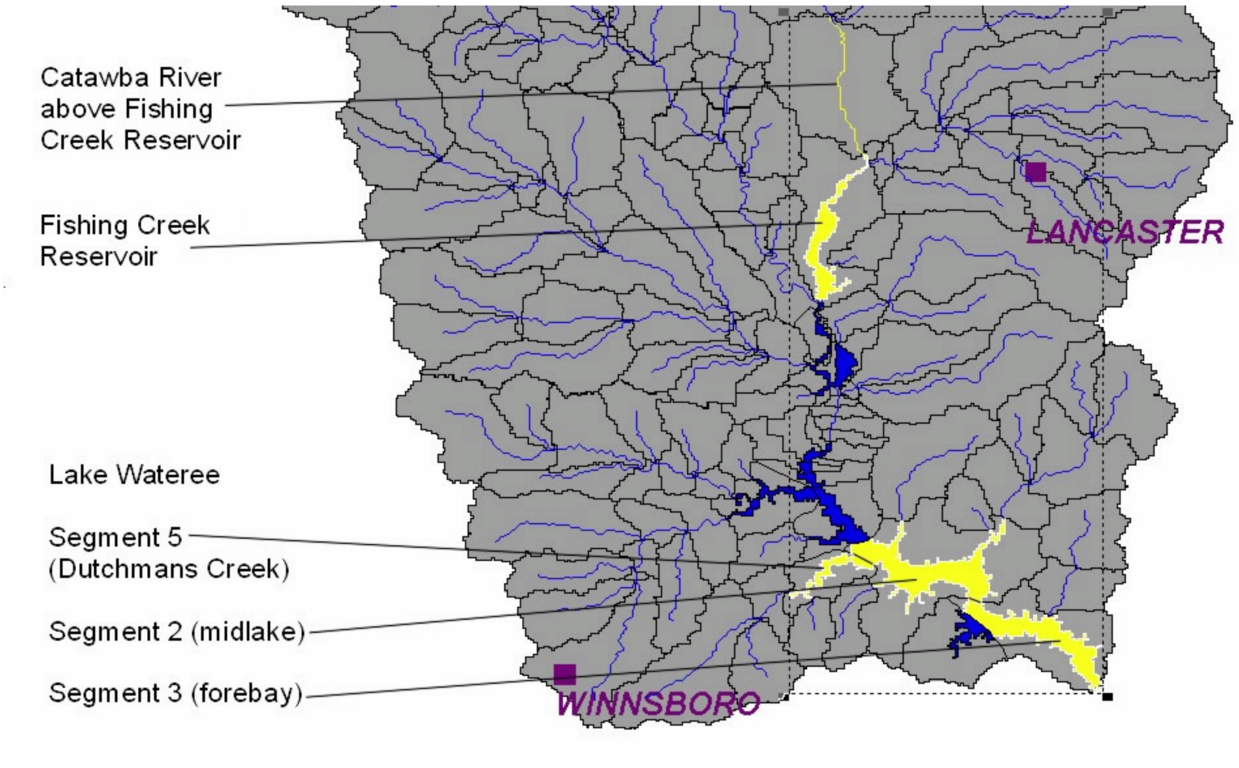


Fig. 6. Image from the WARMF model showing the reservoir segments and river reach used for model calibration, verification testing, and scenario analysis. Lake Wateree overall is divided into 10 segments, but for most there are no observed values to use for statistical testing. This figure also shows how the overall study area is divided into catchments (black lines) and stream reaches (blue lines). Each catchment, stream reach, and reservoir segment can be individually parameterized. Simulation results can be analyzed for stream reaches and catchments.

Model verification

Once the model was successfully calibrated we tested it by simulating the period from January 1, 1993 through August 31, 1995. With the exception of date dependent forcings and loadings (e.g. meteorology and PS discharges), all model coefficients and parameters were left unchanged during the verification execution. During the verification interval there were sufficient observed data for statistical evaluation in 1993 and 1995 in Lake Wateree segments 2, 3, and 5 and the Catawba River above Fishing Creek Reservoir. We used the RMSE comparison and KS test as detailed in the calibration section above.

Management scenarios and exceedence analysis

After calibration and verification testing were completed we ran several additional model simulations using varying levels of phosphorus loading to the lower Catawba River and its reservoirs. Some of the simulations represent actual or planned management activities (such as the implementation of new phosphorus discharge levels) and some represent scenarios of possible future actions; this analysis provides a direct assessment of the possible effect of those actions. A few of the scenarios do not represent realistic management alternatives. They were run only as a way of making a discrete and discernable change in the quantity of total phosphorus loading. A description of each scenario and its effect on phosphorus loading will be provided in the Results section.

We also developed exceedence charts for TOTP and CHLa based on phosphorus loading into Fishing Creek Reservoir. These charts are a rapid assessment method for forecasting how a projected change in phosphorus loading may impact the reservoir with respect to regulatory compliance. An exceedence chart is made by executing the model using the phosphorus load scenarios described above. Then for each simulation we determined the proportion of days the water quality standard, 0.06 mg l^{-1} for TOTP and 40 μg l^{-1} for CHLa, was exceeded.

Phosphorus loss

Phosphorus is not a conservative constituent in the WARMF model. It adsorbs to sediment particles and can be sequestered in the riverbed for varying periods of time during its downstream transport. One implication of this is that the further upstream a load of phosphorus enters the system, the greater the probability a portion of it will be lost to the system for the duration of the simulation.

We quantified this effect using the calibrated model by selecting a major point source discharge well up toward the headwaters of the lower Catawba River system, significantly reducing its phosphorus load, and running the model with no other changes. At each stream reach downriver the instream phosphorus load was calculated and the difference in the two scenarios derived. This load difference in each reach is expressed as a proportion of the initial difference, that is, the difference in the stream reach where the point source discharge occurs.

RESULTS AND DISCUSSION

Calibration

Our final calibration in the Catawba River segments focused on TOTP and TOTN concentrations entering Fishing Creek Reservoir. To calibrate we made parameter adjustments to increase the NPS contribution because the point source loadings (derived from discharge monitoring reports) were not sufficient to simulate observed concentrations. Two adjustments were made. The first was to increase fertilization application based on information from the US Department of Agriculture (USDA), Clemson University, and suggestions from Systech (Table 3). This change increased the amount of fertilizer applied as well as application throughout the year in accordance with southern agricultural practices as described in the above sources. We also made stream buffers 10 m wide with a slope of 1 (m m^{-1}), in contrast to 30 m wide and essentially flat in the base model. This change was made based on personal observation in the study area and

Table 3. Values used to calibrate the WARMF model for TOTP and TOTN in the Catawba River and CHLa, TOTP, and TOTN in the reservoirs.

Target constituent	Model parameter	Calibration value	Source
NPS TOTP, TOTN	Stream buffer width - meters	10	Personal observation and SCDHEC
NPS TOTP, TOTN	Stream buffer slope - unitless	1	Personal observation and SCDHEC
NPS TOTP, TOTN	Fertilization - kg ha^{-1} mo^{-1}	Varies by land use: Pasture (NH4 - 3, PO4 - 1.4), Cultivated (NH4 - 112, PO4 - 90), Low intensity dev. (NH4 - .05, NO3 - .01, PO4 - .1), High intensity dev. (NH4 - .08, NO3 - .03, PO4 - .1), Com/Ind (NH4 - .1, NO3 - 03, PO4 - .1)	http://www.nrcs.usda.gov/technical/land/pubs/wp14text.html, http://www.clemson.edu/agsrvlb/myweb10/interest.htm, Systech Engineering
CHLa	Growth rate - per day	Bluegreen - 1.5 Diatoms - 0.9 Green - 1.5	Bowie et al. (1985)
CHLa	Temperature growth ranges - ^{o}C	Bluegreen - 15-40 Diatoms - 0-35 Green - 5-50	Bowie et al. (1985)

after consulting with Wayne Harden at SCDHEC. We also confirmed the Catawba River discharge calibration above Fishing Creek Reservoir and did nothing to change it.

Calibration in the reservoirs focused on Fishing Creek Reservoir for TOTP and TOTN concentrations, and in Lake Wateree segments 2 and 3 for CHLa, TOTP, and TOTN concentrations. The fit of observed to simulated quarterly means was accomplished by adjusting the temperature growth curves and growth rates for phytoplankton (Table 3).

The simulated and observed values for flow, TOTP, and TOTN in the Catawba River above Fishing Creek Reservoir were a close fit (Figs. 7, 8,9). The correlation coefficient for daily flow was 0.847 (p=.0001) with a RMSE of 42.1. The seasonal fit was also strong, with a p-value for the Kolmogorov-Smirnov test (designated p(KS)) of 0.57 and RMSE of 0.089. These RMSE values are <9% and <7%, respectively, of the range of the data. The largest discrepancies in the daily values occur at periods of a rapid large increase or decrease in flow.

Simulated and observed values for TOTP and TOTN also fit well (p(KS) = 0.57). The number of observed values ranges from 2 to 4 per season, versus 90 to 92 for the simulated values, so variability in the data is more apparent for the observed values. Seasonality in the observed concentrations is clearly replicated in the simulated concentrations. The relatively large RMSE for both constituents is caused by the more frequent and higher peaks typically seen in the simulated values.

Calibration of TOTP and TOTN concentrations in Fishing Creek Reservoir also produced a good fit (Fig. 10, 11). The TOTP fit was especially strong (p(KS) = .988). The primary discrepancy was during summer 1997 when a large concentration peak caused by an upstream storm event was not seen in the observed data. The TOTN result was weak, caused by general under-prediction of observed values. Under-prediction of TOTN was also seen in the Catawba River inflow (Fig. 9), suggesting that upstream NPS sources of nitrogen are not fully represented in the model. There were no observed TOTP values after spring 1998 and there were not enough observed CHLa values to calibrate that constituent in Fishing Creek Reservoir.

For Lake Wateree segment 2 the calibration results were strong for CHLa (p(KS) = .699) and TOTP (p(KS) = .808), and weak for TOTN (p(KS) = .046) (Figs. 12, 13, 14). The seasonal trends were clearly seen in CHLa and TOTP, and the under-prediction of TOTN observed in upstream portions are continued in this segment. In Lake Wateree segment 3 the fit is good for CHLa (p(KS) = .699), weak for TOTP (p(KS) = .01), and good for TOTN (p(KS) = .139) (Figs. 15, 16, 17). In segment 5 the fit for CHLa (p(KS) = .893) and TOTP (p(KS) = .164) was strong and it was weak for TOTN (p(KS) = .0023) (Figs. 18, 19, 20). The fit for TOTP would have been much stronger (p(KS) = .336) but for the anomalously large mean concentration in winter 1998. This does not cause a problem during winter, but it may be a partial cause of the large CHLa concentrations predicted for Spring 1998.

Overall the calibration results in Lake Wateree suggest algal dynamics are fairly well represented, but that there is differentiation in nutrient processes among locations that the model is not picking up. In general the model is effective at simulating major trends, but details are frequently missed. As with the interpretation of most models, it is important to recognize that the

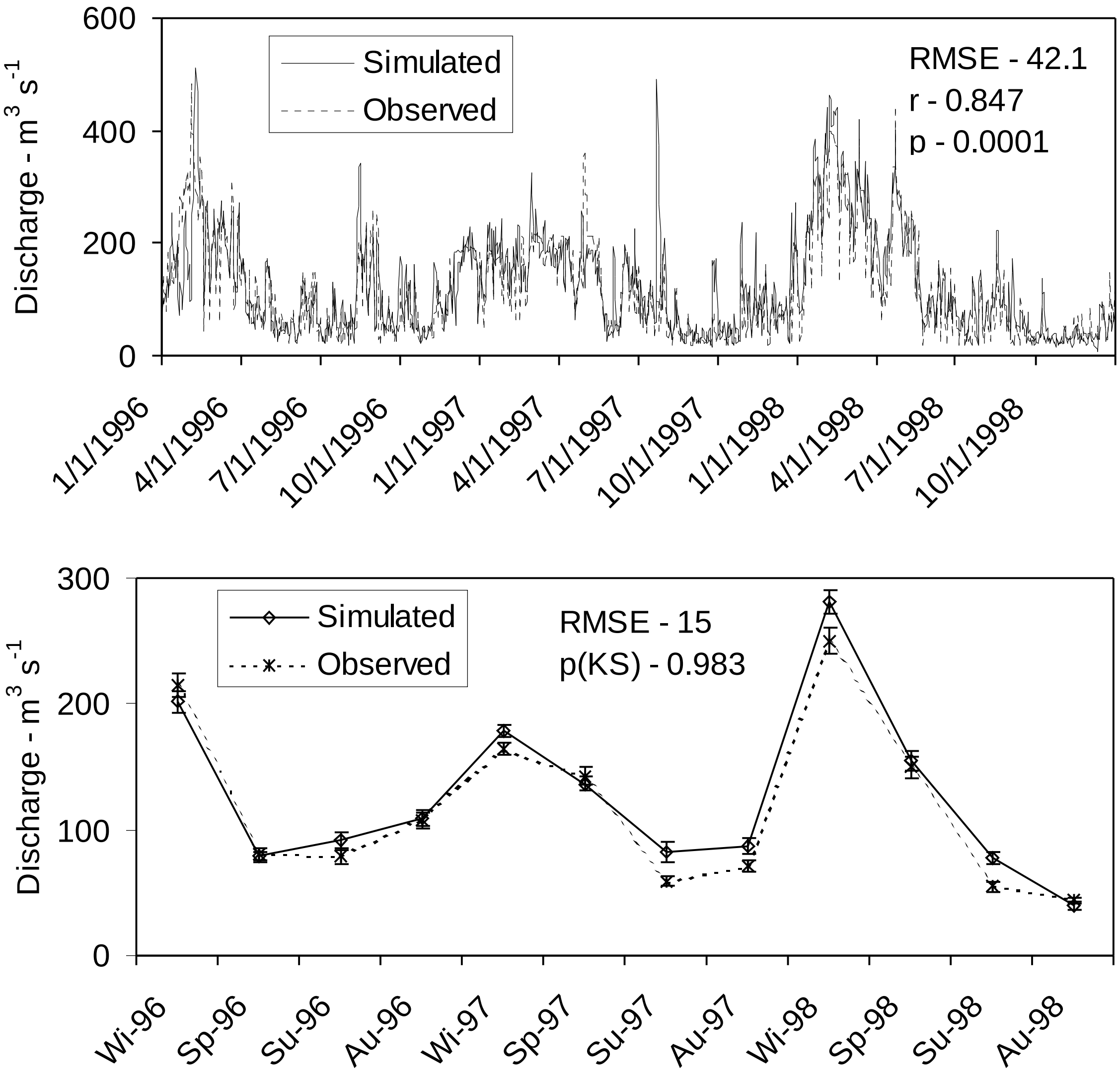


Fig. 7. Calibration charts for daily (top) and quarterly ± standard error (s.e.) (bottom) discharge for the Catawba River above Fishing Creek Reservoir.

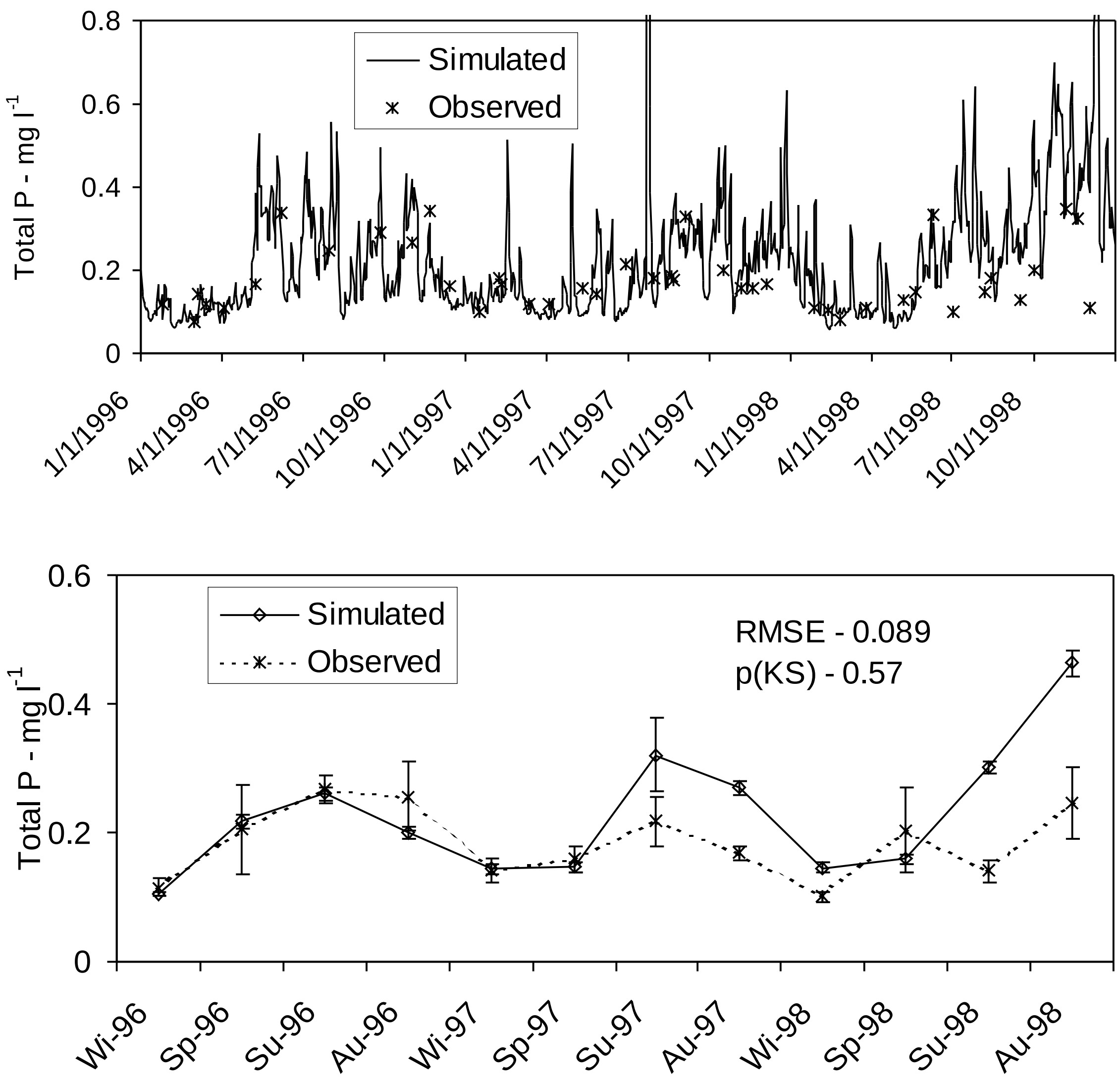
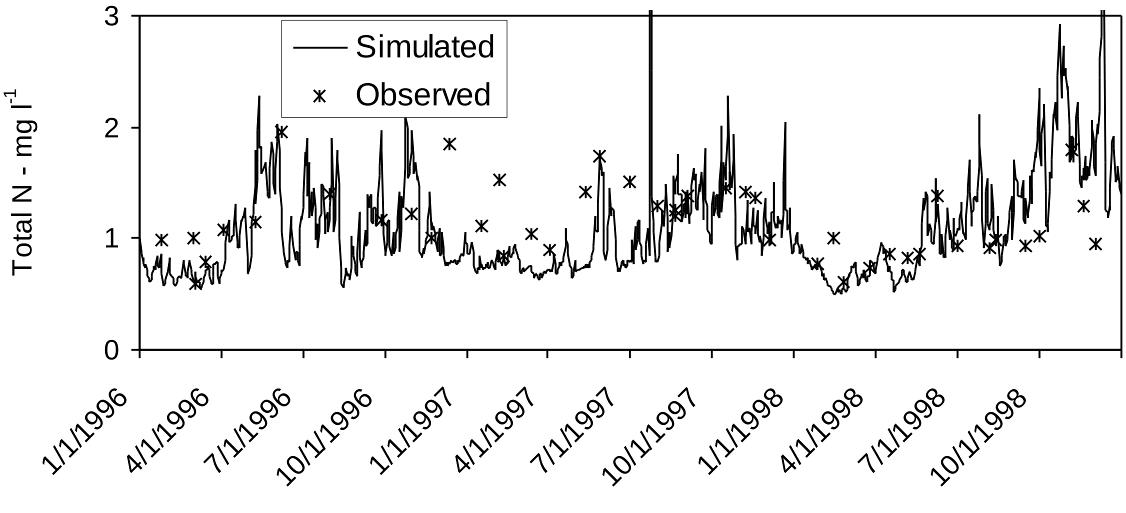


Fig. 8. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTP concentrations in the Catawba River above Fishing Creek Reservoir.



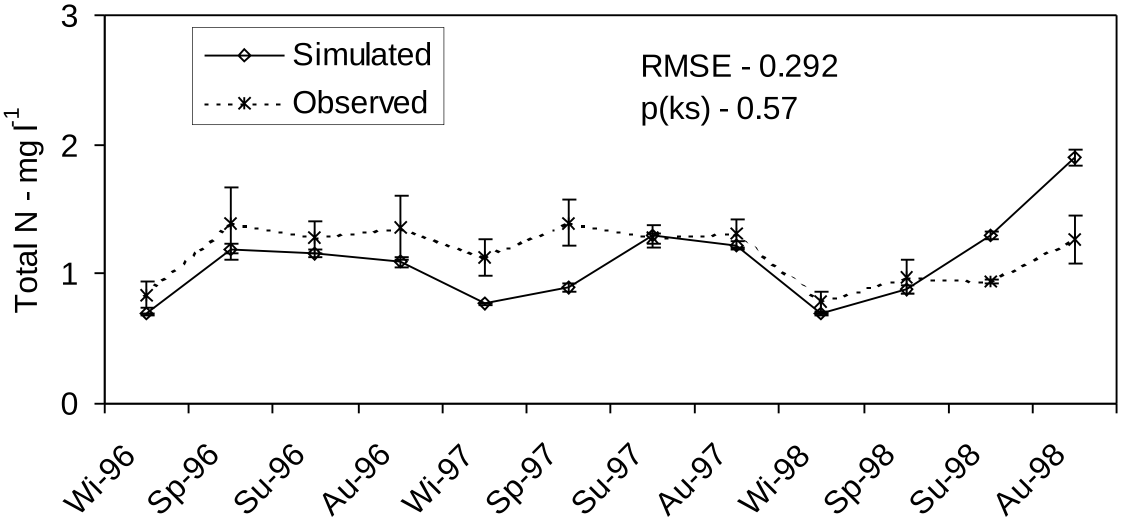


Fig. 9. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTN concentrations in the Catawba River above Fishing Creek Reservoir.

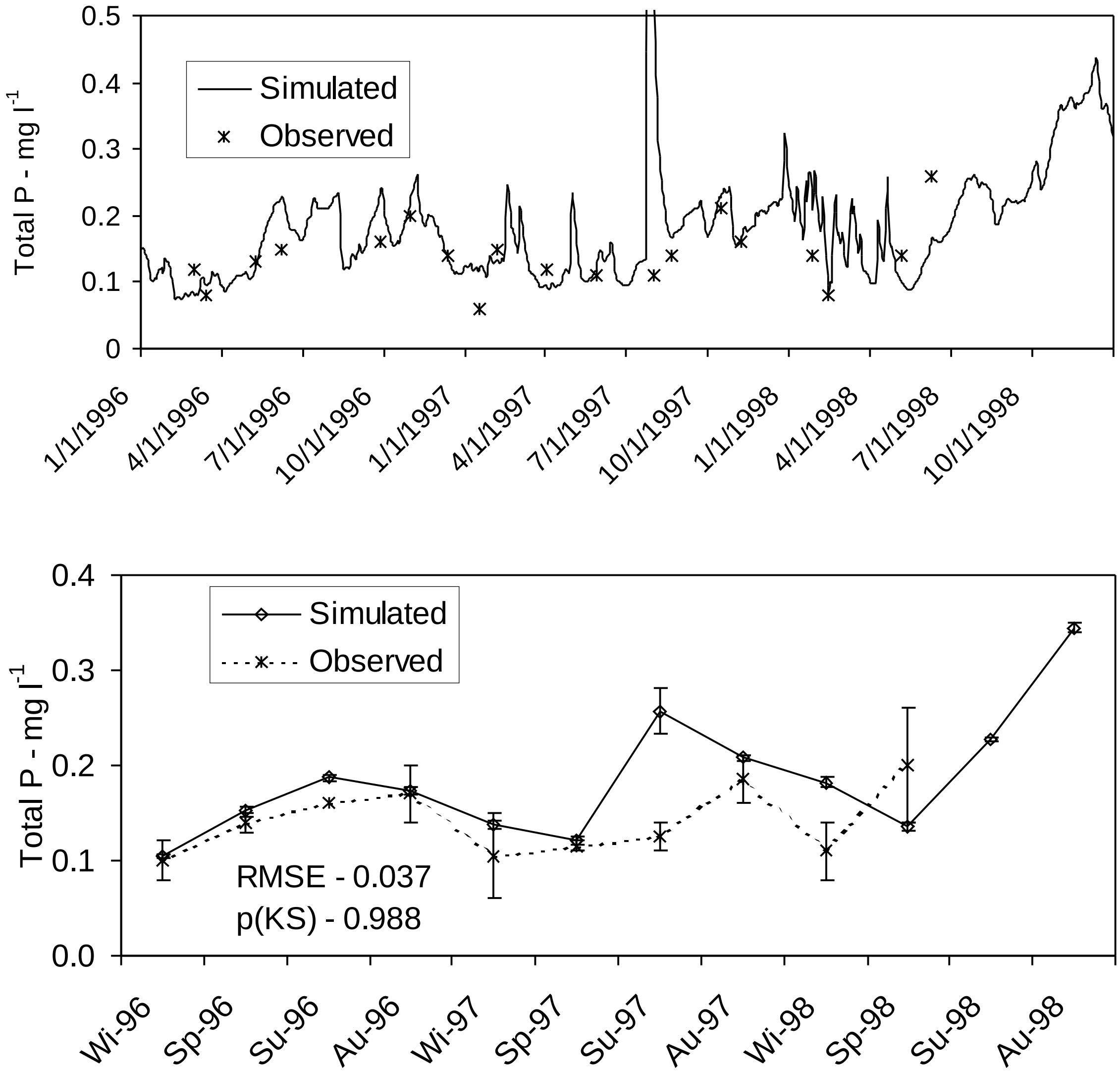


Fig. 10. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTP concentrations in Fishing Creek Reservoir.

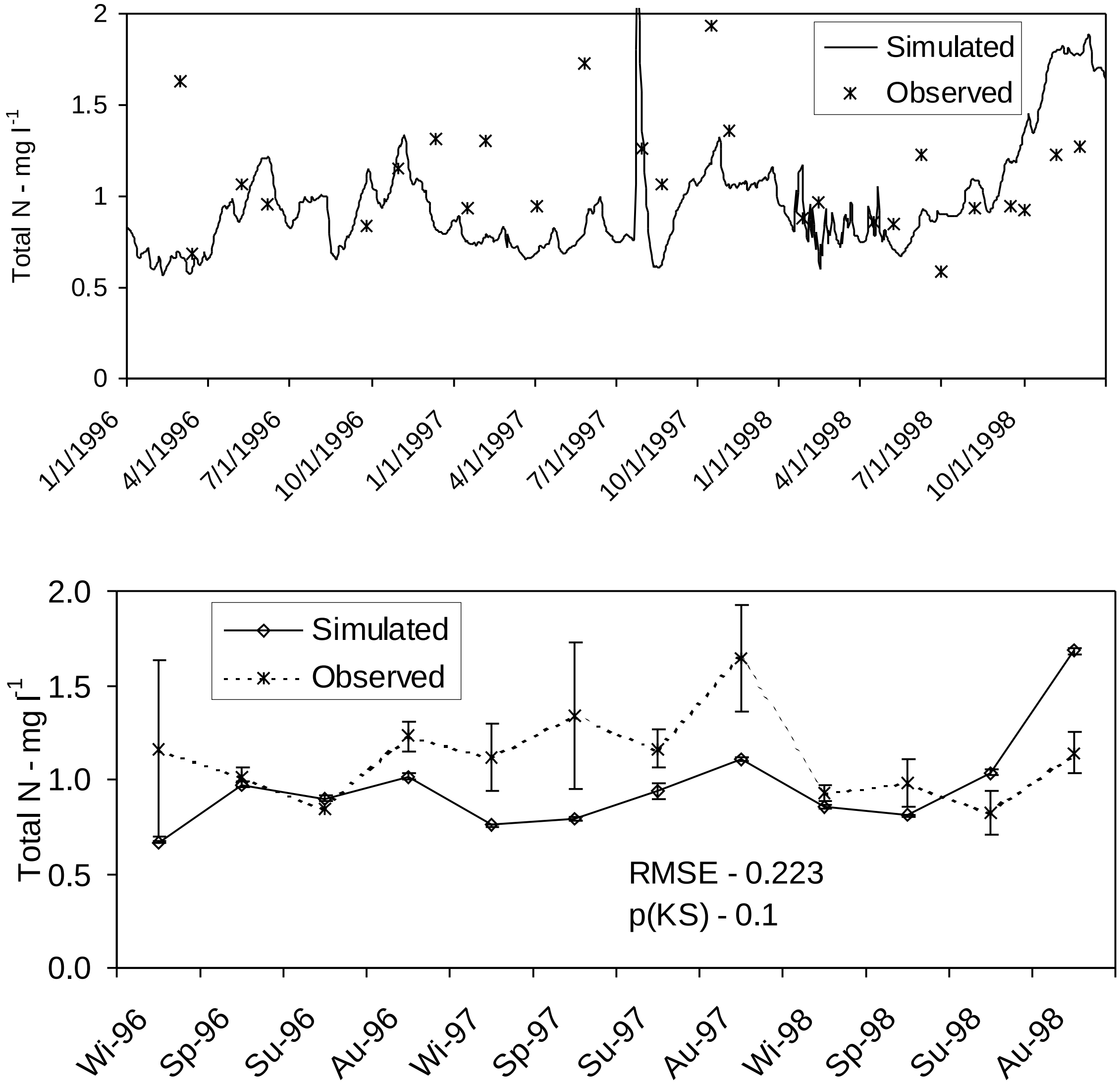


Fig. 11. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTN concentrations in Fishing Creek Reservoir.

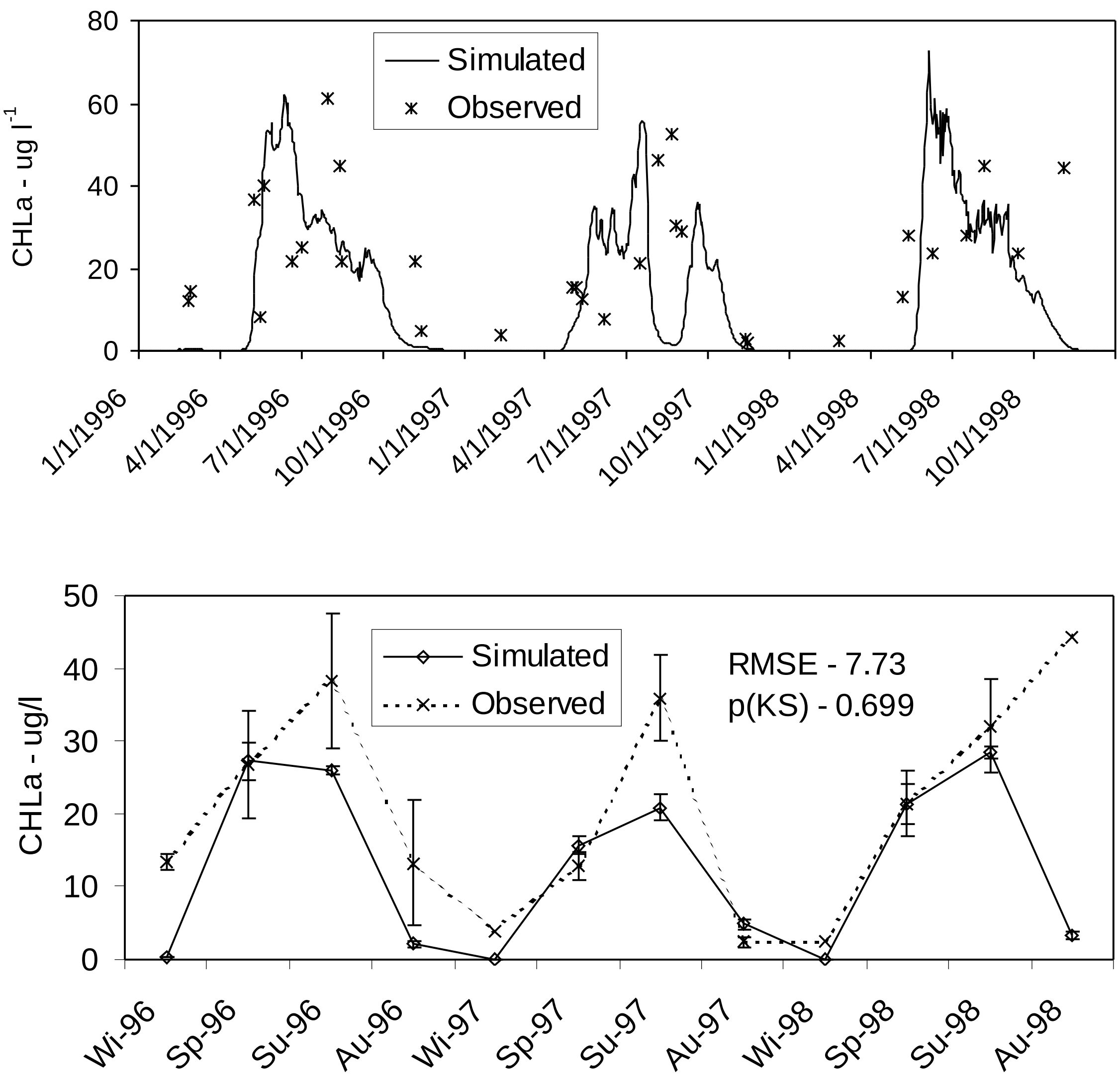


Fig. 12. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for CHLa concentrations in Lake Wateree segment 2.

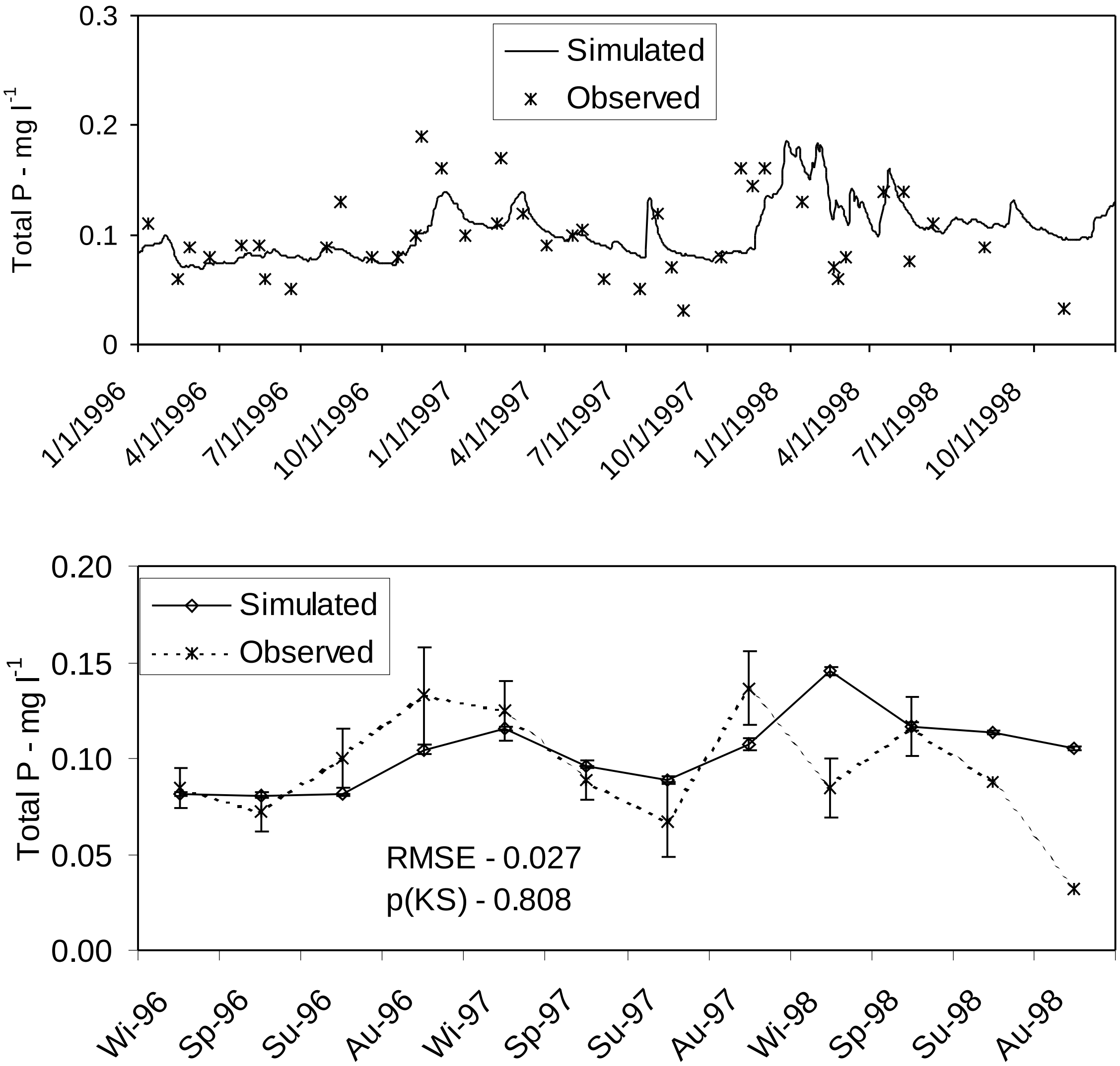


Fig. 13. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTP concentrations in Lake Wateree segment 2.

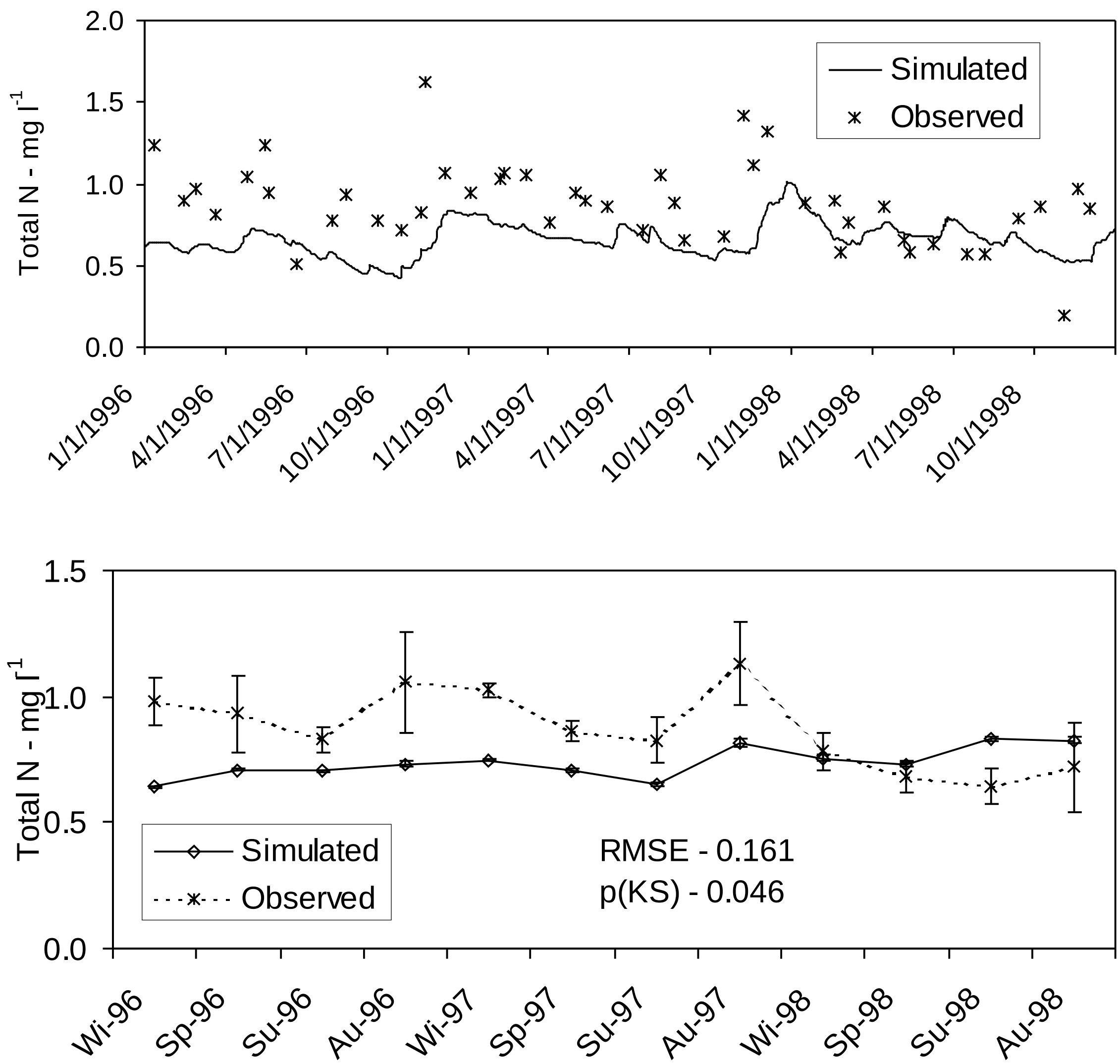


Fig. 14. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTN concentrations in Lake Wateree segment 2.

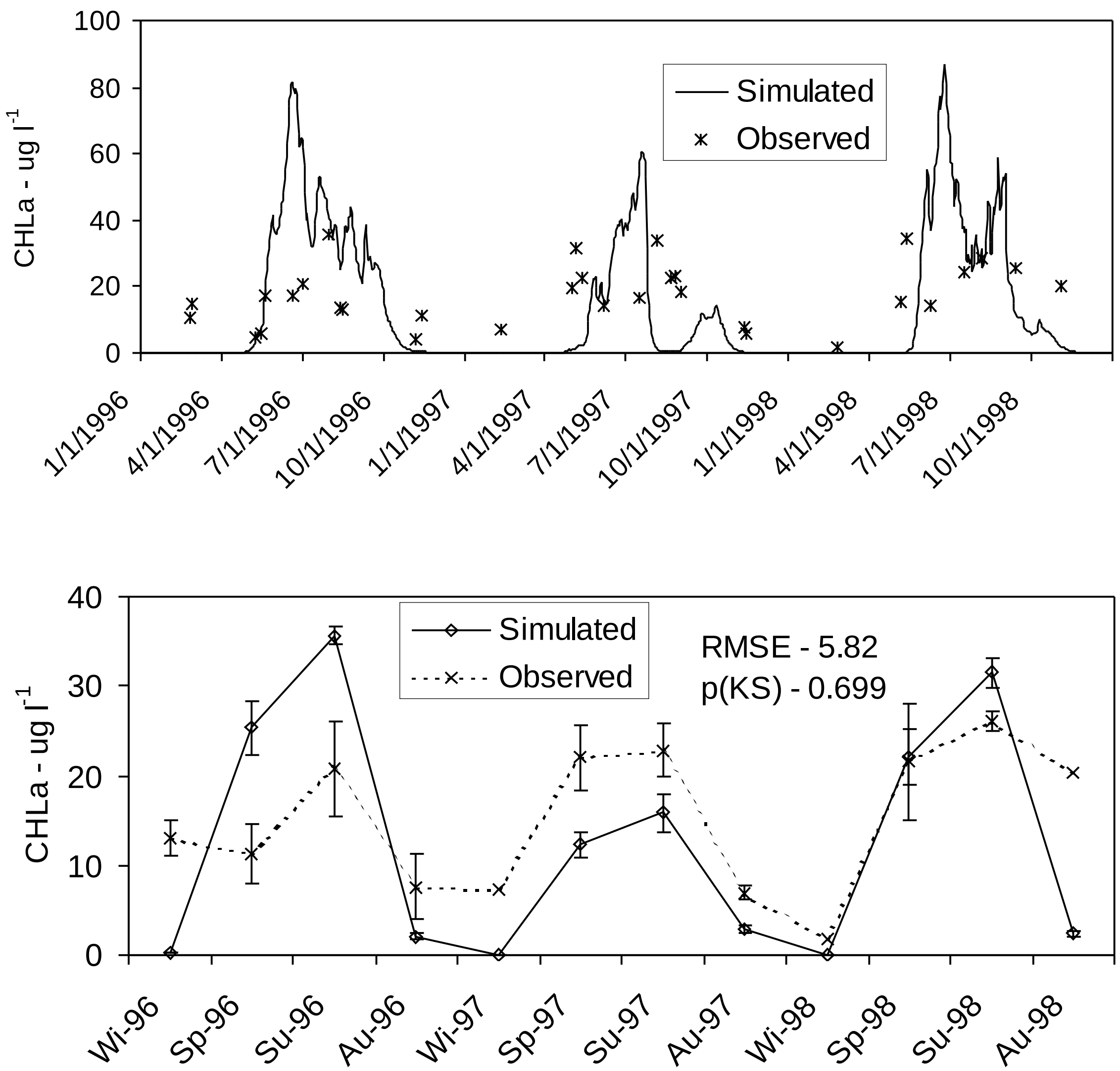


Fig. 15. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for CHLa concentrations in Lake Wateree segment 3.

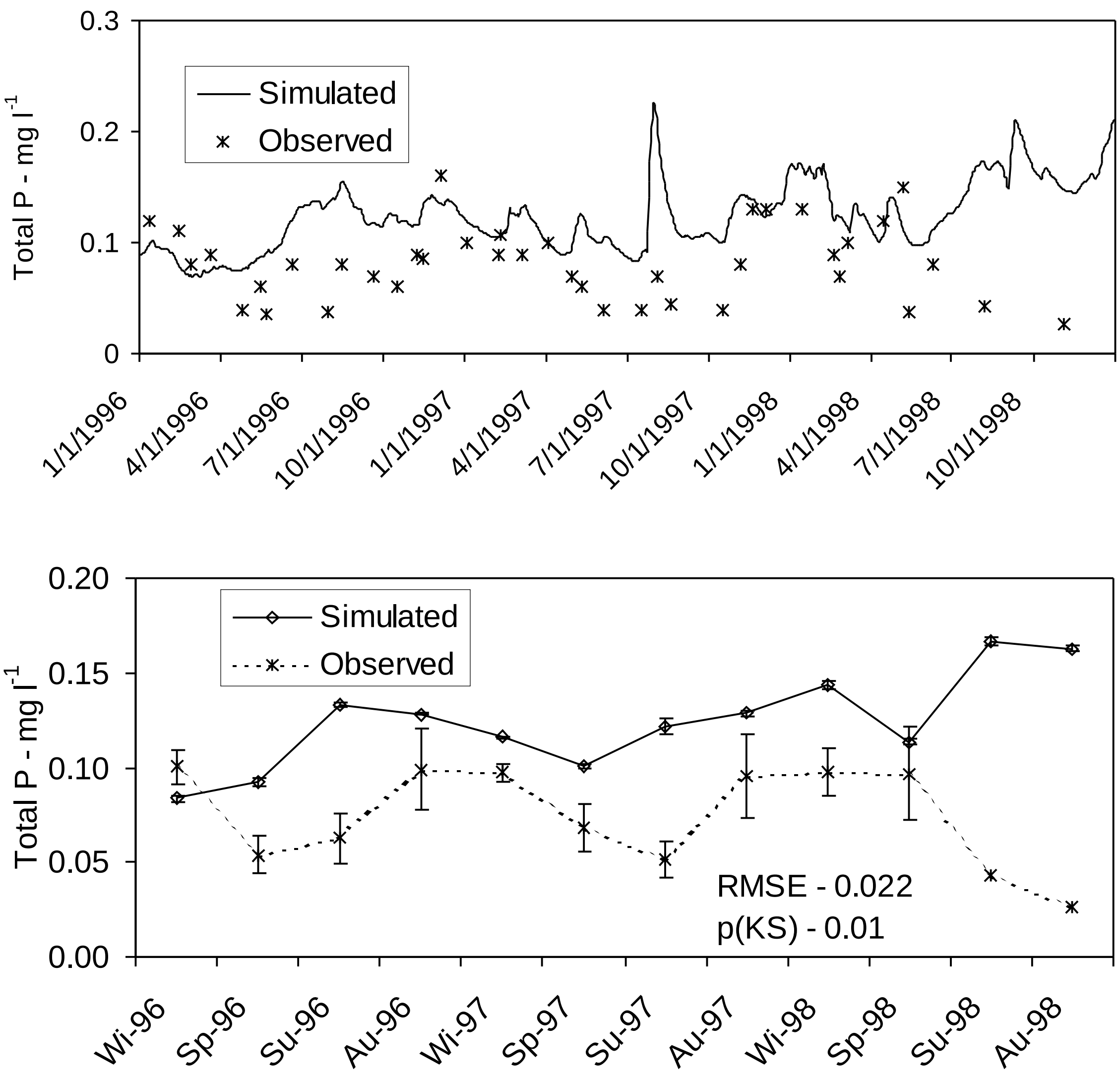
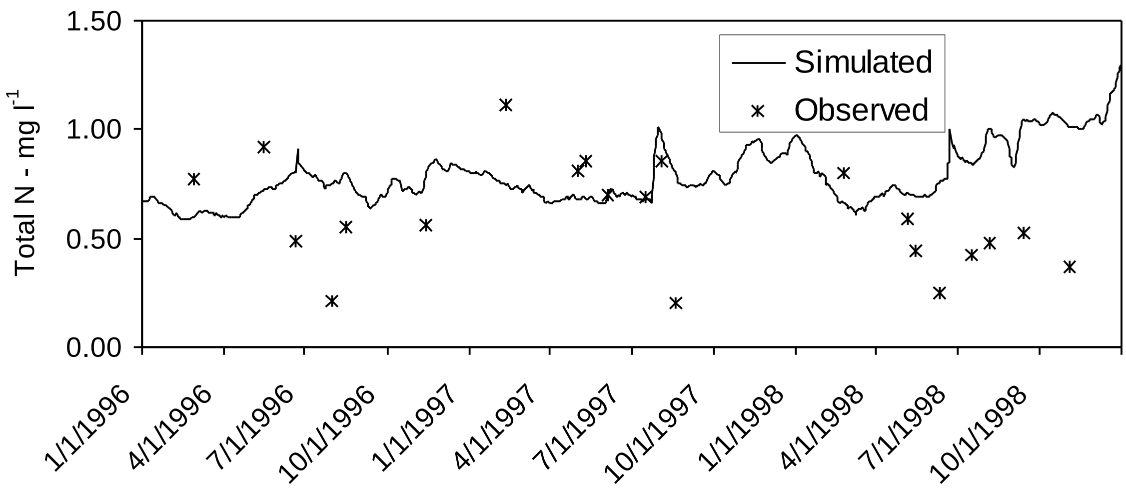


Fig. 16. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTP concentrations in Lake Wateree segment 3.



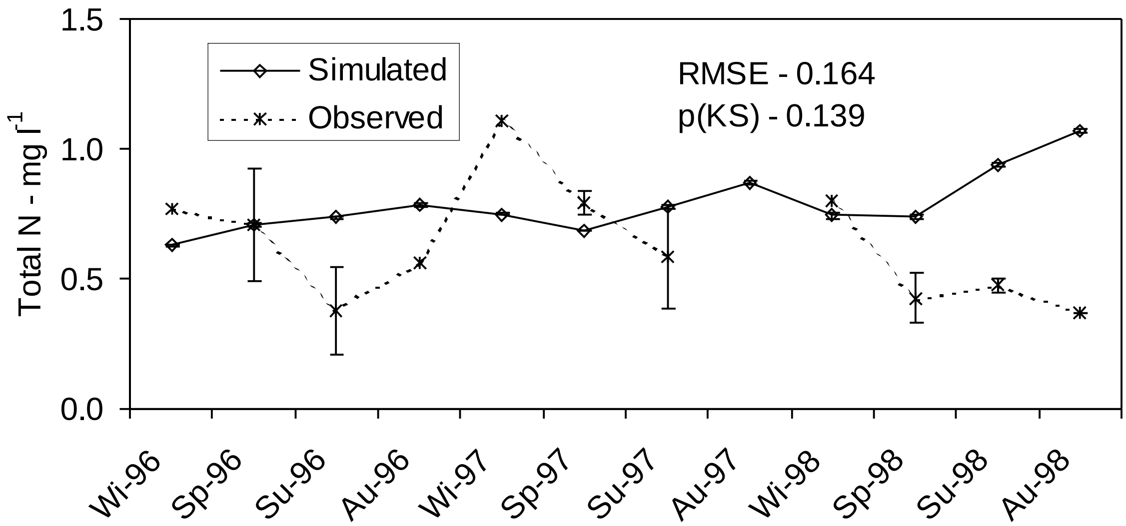


Fig. 17. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTN concentrations in Lake Wateree segment 3.

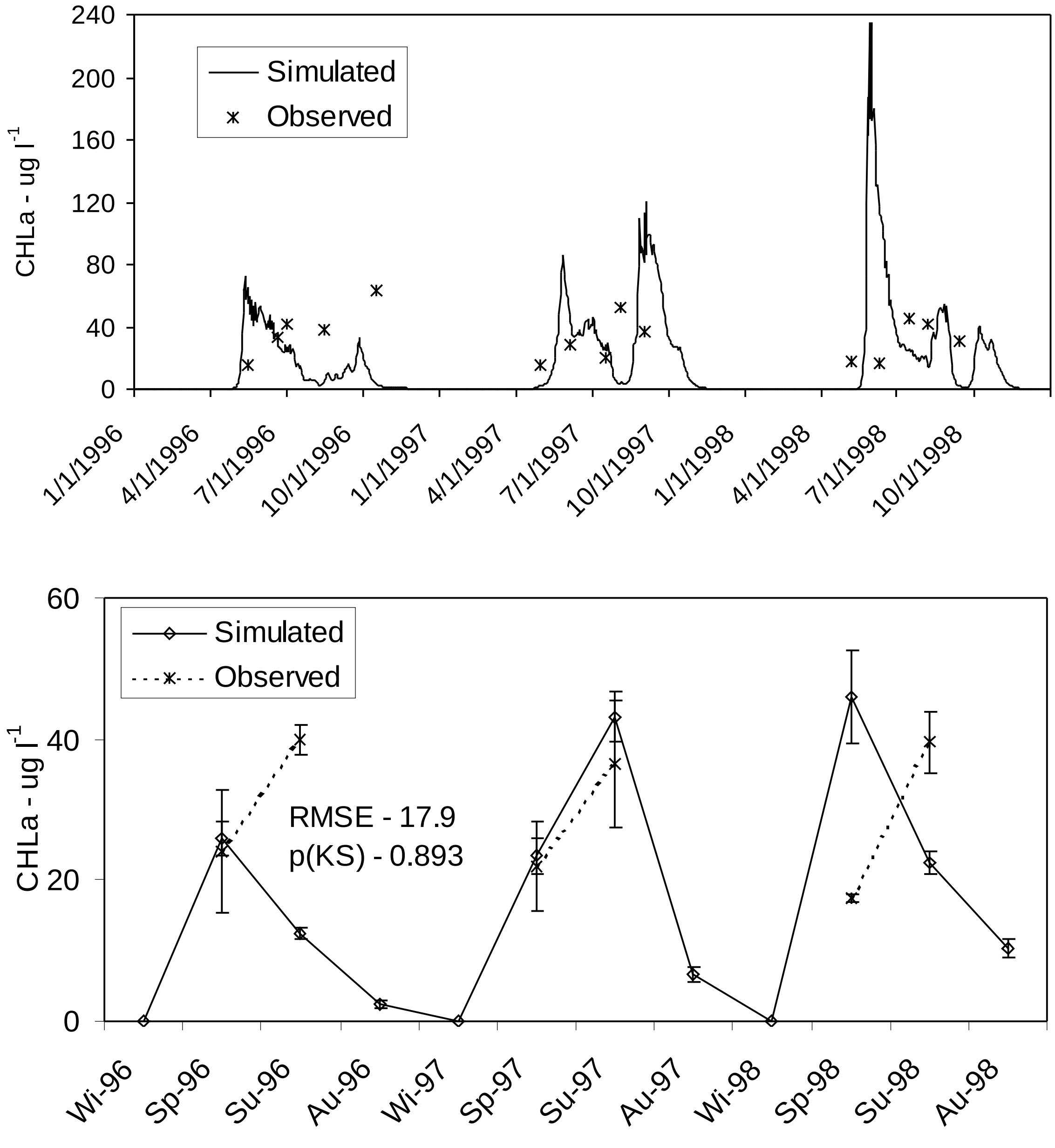
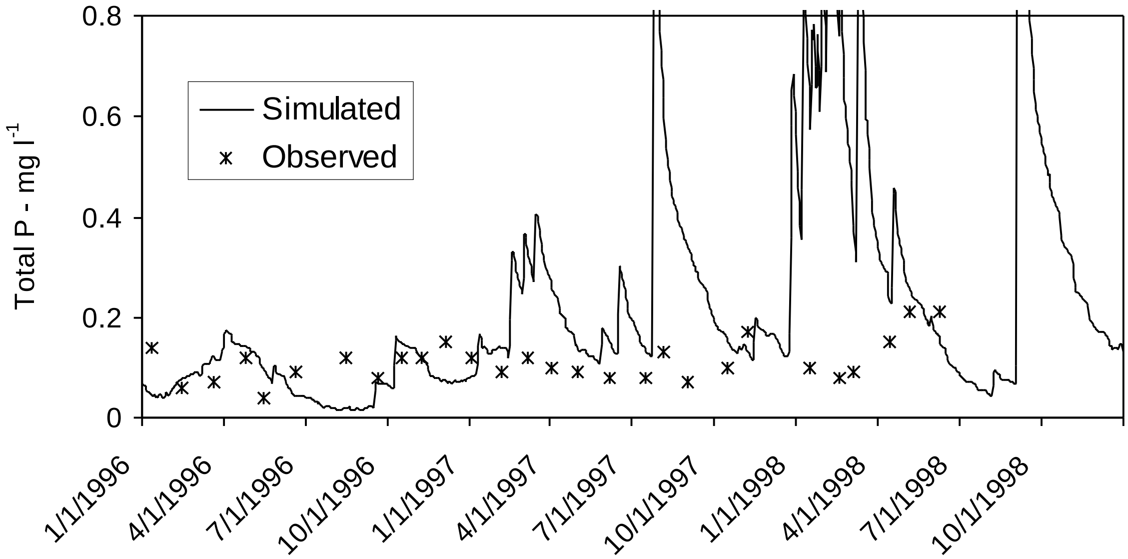


Fig. 18. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for CHLa concentrations in Lake Wateree segment 5.



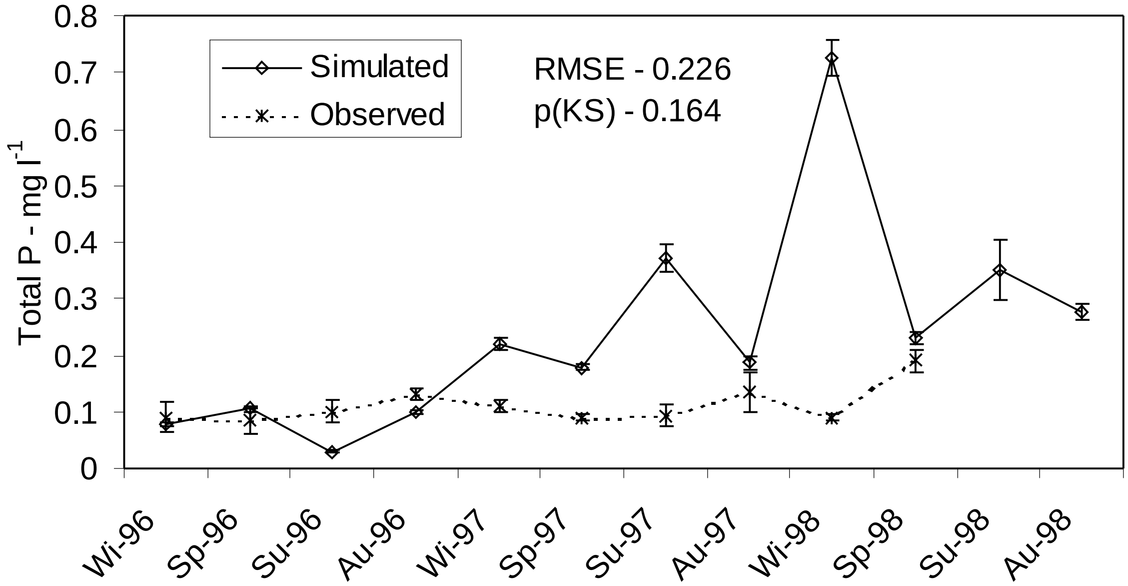


Fig. 19. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTP concentrations in Lake Wateree segment 5.

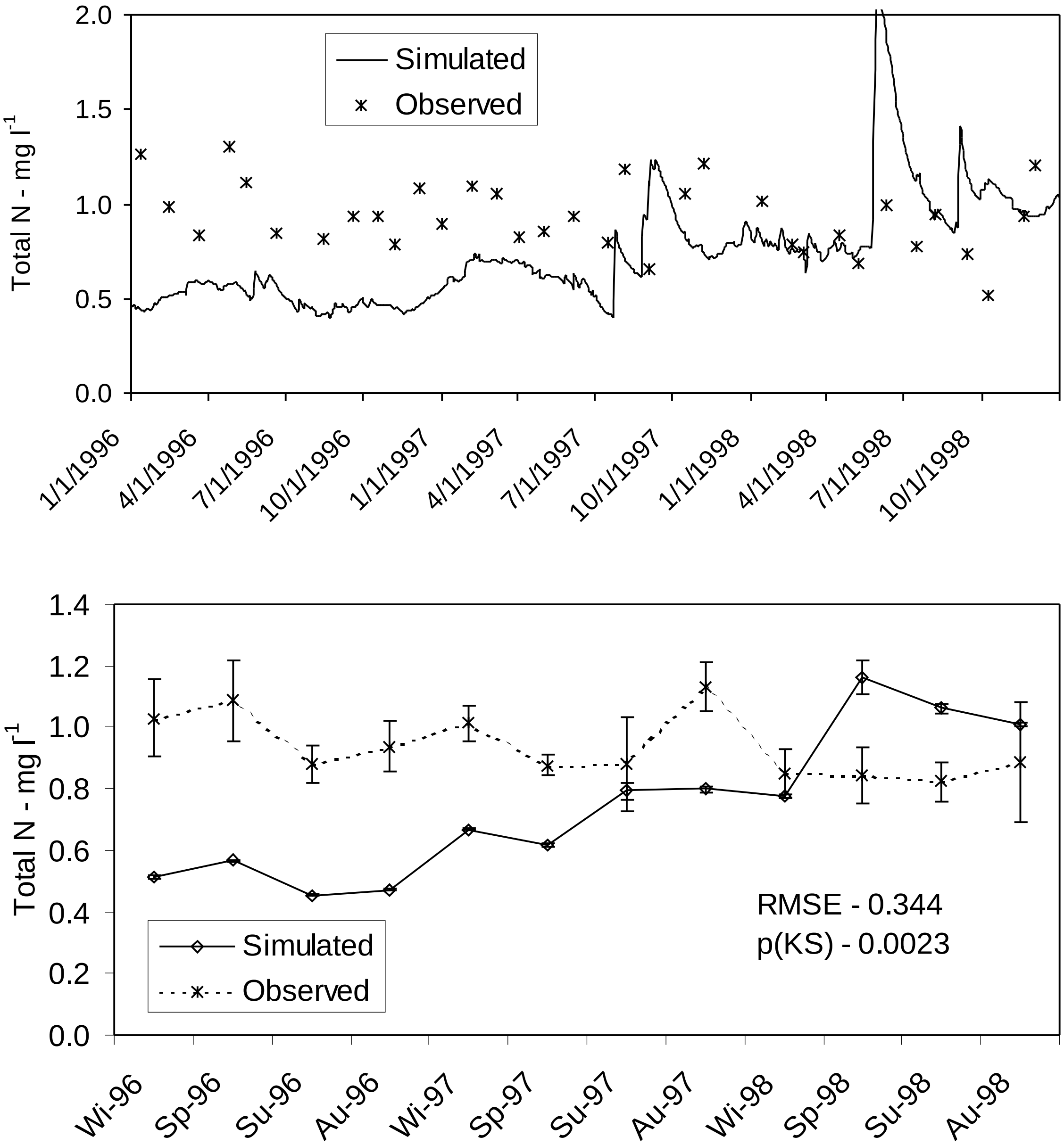


Fig. 20. Charts showing observed and simulated values (top) and quarterly calibration ± s.e. (bottom) for TOTN concentrations in Lake Wateree segment 5.

field data are sparse in space and time and may not represent the actual state of the waterbody being monitored. The model, however, is simulating numerous complex and interdependent processes that are well understood broadly in the environment but are less well understood in specific locations without a prohibitive investment in human, field, and laboratory resources. Both these factors suggest some caution in evaluating these results as well as the likelihood that more accurate models could be produced at this scale.

Lake Wateree has several small tributary embayments like Dutchmans Creek (segment 5) that are of concern to local residents because of possible locally severe water quality problems. Embayments can be environmentally distinct (e.g. hydrology, temperature) from the mainstem and thus exhibit different water quality responses (Kennedy and Walker, 1990; Tufford and McKellar, 1999). This is one reason the Lake Wateree model includes separate segments for three of the major embayments. Our results suggest the embayment simulations for unmonitored locations are useful for estimating broad trends and relationships, but are less accurate for detailed views.

Verification

There was sufficient observed data in an independent data set (1992-1995) to perform verification testing for flow, TOTP, and TOTN in the Catawba River above Fishing Creek Reservoir, and for CHLa, TOTP, and TOTN in Lake Wateree segments 2, 3, and 5. The fit between simulated and observed values in the Catawba River was very strong for flow and TOTN; for TOTP it was weak (Table 4). The largest fractional source of phosphorus in the lower Catawba River is coming from Sugar Creek because of several major municipal discharges. The fit there between simulated and observed values for TOTP was strong (p(KS) = .879, Table 4), suggesting the over-prediction just above Fishing Creek Reservoir may be NPS related.

The verification results in Lake Wateree were similar to the calibration results in that the fit for CHLa was good in all three segments, the fit for TOTP was good in segments 2 and 5, and other nutrient results were weak (Table 4). Given the correspondence with the calibration results we consider the model to be useful for simulations that forecast the possible effect of changes in watershed nutrient loading. Interpreting further simulation results in Lake Wateree should be cognizant of the situation that different locations in the lake have differing environments and responses to forcing functions. Also that verification was not possible for Fishing Creek Reservoir, which is the first reservoir to receive and process Catawba River nutrient loads.

Management scenarios and exceedence analysis

This model was developed as a tool for SCDHEC to use in forecasting the possible effect of changes in total phosphorus loading to the lower Catawba River watershed. The reservoirs appear on the South Carolina 303(d) list because of phosphorus impairment, indicating exceedence of the phosphorus criterion. It is unlikely that lake users will directly observe phosphorus impairment, but a frequent effect of excess phosphorus loading is high

Table 4. Statistics from the verification testing of the model. Simulations were runs for 1992 – 1995. See text for discussion.

Parameter	Waterbody	KS p-value	RMSE
CHLa	Wateree 2	0.699	5.6
TP	Wateree 2	0.938	0.03
TN	Wateree 2	0.056	0.357
CHLa	Wateree 3	0.211	12.578
TP	Wateree 3	0.006	0.0559
TN	Wateree 3	0.076	0.2579
CHLa	Wateree 5	0.819	19
TP	Wateree 5	0.206	0.207
TN	Wateree 5	0.0059	0.269
Flow - quarterly	Catawba R	0.996	21.03
TP	Catawba R	0.010	0.13
TN	Catawba R	0.996	0.519
TP	Sugar Cr	0.879	0.6

concentrations of phytoplankton which at times can be observed both directly (e.g. algal blooms) and indirectly (e.g. malodorous water). For these reasons we developed exceedence charts of both TOTP and CHLa for Fishing Creek Reservoir and the mainstem of Lake Wateree as represented by model segment 2 (Fig. 21). Some of the scenarios (Table 5) include the effect of recent permit changes to municipal and industrial discharges in both North and South Carolina; a net reduction of approximately 375 kg d^{-1} (Table 6).

The TOTP exceedence chart indicates that phosphorus loading is significantly in excess of what the lakes can accept and still be within criteria. Fishing Creek Reservoir, in particular, is receiving excess loading to the extent that a 25% reduction in loading is needed just to get the exceedence below 100%. Lake Wateree shows a similar step function for total phosphorus exceedence, but it is not as extreme.

The CHLa exceedence chart is similar to TOTP in the sense that it is not linear. Particularly for Fishing Creek Reservoir a substantial reduction in TOTP loading must occur before there is a significant decline in CHLa exceedence. This suggests that the bioavailable fraction of total phosphorus is in excess of what can be utilized by phytoplankton for growth.

Greater CHLa exceedence in Fishing Creek Reservoir than Lake Wateree seems counterintuitive, given the greater residence time in the larger lake. We could not calibrate CHLa in Fishing Creek Reservoir for lack of field data, but in the present context it is worth noting that the largest CHLa observation (87.6 $\mu g\ l^{-1}$) in any lake station during the 1995 – 2000 simulation interval was from Fishing Creek Reservoir in August 2000, and other high concentrations were also observed. This

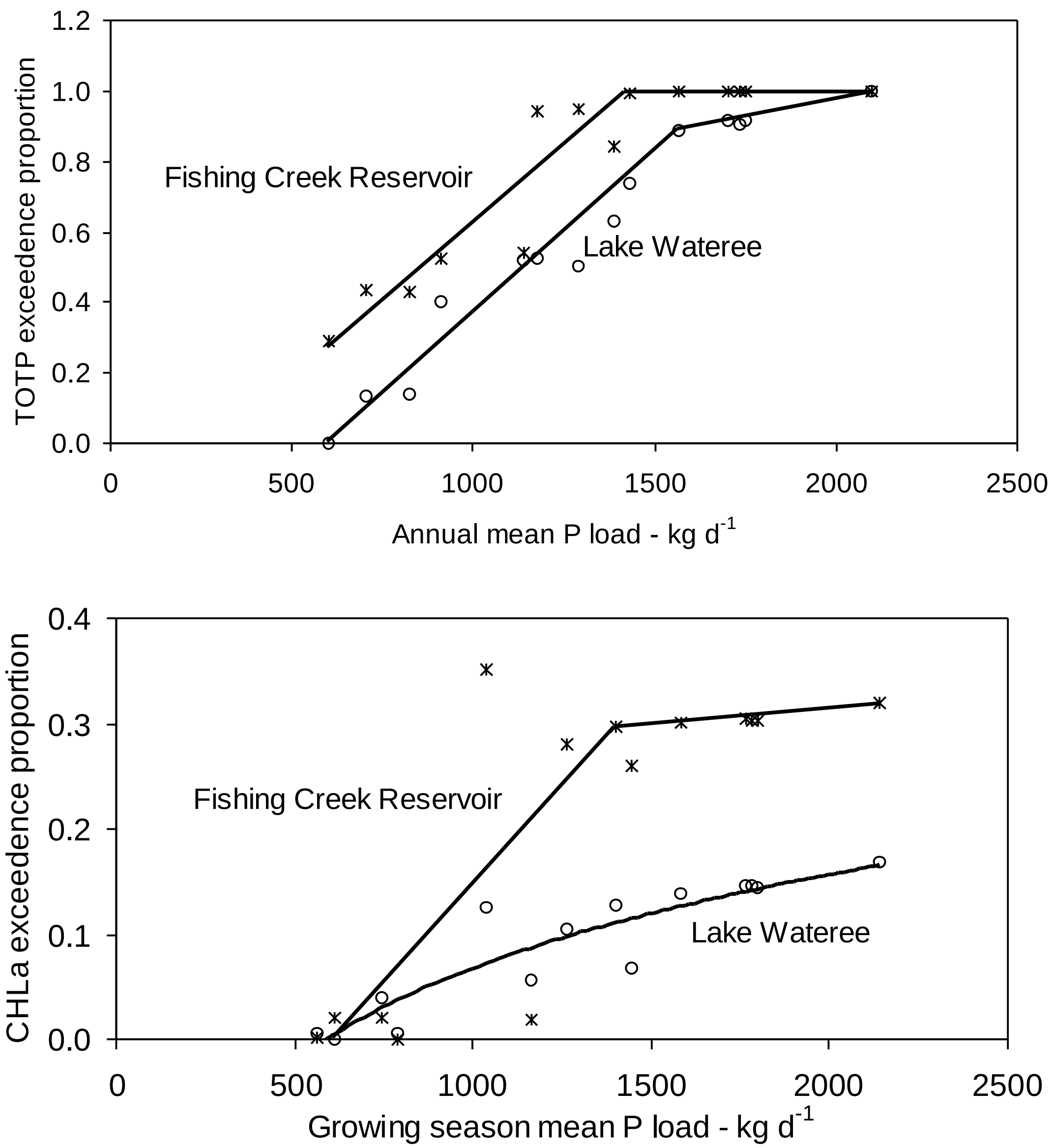


Fig. 21. Exceedence charts for TOTP (top) and CHLa (bottom) in Fishing Creek Reservoir and Lake Wateree. The TOTP exceedences are plotted against the mean daily TOTP load into Fishing Creek Reservoir during the 3-year simulations. The CHLa exceedences are plotted against the mean daily TOTP load into Fishing Creek Reservoir during the growing season (May through October). The lines on the charts are fitted to the scatter of actual values.

Table 5. Scenarios used to develop the exceedence charts and to test management scenarios. The TOTP loads are in kg d-1 and the exceedences are proportions in Fishing Creek Reservoir (FCR) and Lake Wateree (LW). The TOTP load for the TOTP exceedences is the daily mean load for the entire three-year simulations. For CHLa it is the daily mean load during the growing season. See text for discussion.

Scenario	Description	TOTP exceedence			CHLa exceedence		
		P load	FCR	LW	P load	FCR	LW
1	Calibrated model	2097	1.000	1.000	2143	0.319	0.168
2	Scenario 1 and CMU and SC discharging at new permit levels	1754	1.000	0.915	1784	0.303	0.145
3	Scenario 1 and CMU discharging at new permit levels	1737	0.999	0.903	1801	0.303	0.143
4	Scenario 3 and 10 m buffers along 90% of stream channels	1702	1.000	0.914	1766	0.304	0.145
5	Scenario 4 and fertilization reduced by 1/3	1567	0.998	0.889	1583	0.301	0.139
6	Scenario 4 and fertilization reduced by 2/3	1431	0.991	0.737	1401	0.297	0.127
7	Scenario 1 and zero P discharge from CMU	1389	0.840	0.631	1445	0.259	0.067
8	Scenario 6 and SC PS cut by 50% from new permit levels	1293	0.947	0.504	1264	0.281	0.105
9	Scenario 8 and impervious surfaces cut by 50%	1176	0.944	0.527	1040	0.351	0.125
10	Scenario 7 and zero P discharge from SC PS	1139	0.543	0.517	1162	0.018	0.056
11	Scenario 10 and impervious surfaces reduced by 50%	912	0.526	0.401	744	0.020	0.040
12	Scenario 6 with zero P discharge from CMU and SC PS	822	0.432	0.139	788	0.000	0.005
13	Scenario 12 with impervious surfaces reduced by 50%	703	0.433	0.136	565	0.002	0.005
14	Scenario 10 and NPS loading reduced to near zero	603	0.289	0.000	614	0.020	0.000

Table 6. Point source phosphorus loads in the base (calibrated) model, and new loads that will be effective when compliance with new permits is achieved.

NPDES	Name	Base model		New permit	
		kg d^{-1}	lb d^{-1}	kg d^{-1}	lb d^{-1}
NC0024937	Sugar Cr	301.8	665.3	75.7	166.9
NC0024945	Irwin Cr	59.5	131.1	56.8	125.2
NC0024970	McAlpine Cr	411.3	906.7	242.3	534.1
SC0001015	Bowater	121.3	267.5	132.4	291.9
SC0001783	Hoechst-Celanese [a]	55.5	122.4	--	--
SC0003255	Springs Industries [a]	4.2	9.2	--	--
SC0020371	Fort Mill	6.3	13.8	5.7	12.6
SC0020443	Rock Hill Manchester	63.6	140.3	56.5	124.6
SC0021211	Great Falls	1.8	4.0	5.4	11.9
SC0036056	Chester	2.4	5.3	5.1	11.2
SC0038156	York Fishing Creek	2.4	5.4	7.7	17.0
SC0046892	Lancaster Catawba R	14.4	31.7	21.8	48.1
Total		1044.5	2302.7	669.0	1475.0

[a] A new permit was not in place at the time of model development.

suggests that the phytoplankton communities in Fishing Creek Reservoir are able to rapidly respond to periods of low flow (longer residence time) and high concentrations of phosphorus.

These exceedence charts do not match those that would be derived using only observed data. The primary reason for this is that the observed values do not include most of the peaks, including the rises and declines, that the simulations produced. This highlights one of the reasons that simulation models are used as an aid in understanding and managing complex systems. The frequency of field monitoring needed to observe all the important variability of a river/reservoir system is prohibitive. Models can provide a more complete view of the system. One implication of this, however, is that indicator metrics derived using simulation results in one case and monitoring data for another, may not match.

The exceedence charts can be used to estimate the effect in the reservoirs of a change in TOTP load into Fishing Creek Reservoir from the Catawba River. Interpretation of the estimated effect must consider that these are not straight-line relationships. There are two primary reasons for this. The first is that phosphorus is not a conservative constituent in the model. This will be discussed in greater detail in a later section, but for now the implication is that the closer a loading change is to the reservoir the greater its effect will be. So a unit change in phosphorus loading will have its maximum effect if it occurs very near Fishing Creek Reservoir, and its minimum effect if it occurs in one of the far upstream reaches of the watershed.

The second reason the exceedence relationships are not linear is that all loads are not temporally equivalent. Large nonpoint source loads are flashy because they are associated with storm runoff events. Point source loads, while they may show a great deal of variability, are much more consistent than nonpoint source loads. So a management scenario targeting NPS loading will not have a unit equivalent downstream effect as one targeting PS loads (Table 5).

The most striking example of this can be seen by examining scenarios 8 and 9. Scenario 9 reduced impervious surfaces in developed areas by 50%, which reduced the TOTP load by 117 kg d^{-1}. Yet both the TOTP and CHLa exceedences increased. In this situation the TOTP concentrations during runoff hydrographs are significantly reduced, but the baseflow concentrations increase (Fig. 22**.** This results in greater continuous loading during periods of lower stream discharge, even though pulse loads from storms events have decreased. Under this scenario the overall result is a decrease in phosphorus loading, but it is conceivable that a net increase could also be observed in other circumstances.

Greater baseflow concentrations in this example probably also helps explain that the CHLa exceedence in Fishing Creek Reservoir is larger in scenario 9 than even the base calibrated model (scenario 1), even though there is substantially less TOTP loading. With less impervious surfaces in scenario 9 more precipitation infiltrates and enters stream channels after a delay as groundwater discharge. This water will have less particulate and more dissolved phosphorus, which in general is more bioavailable. The model shows decreases in streamflow during runoff events and small increases during baseflow, a result that is expected from a reduction in impervious surface cover (Fig. 23).

We should point out that we do not suggest a watershed-wide 50% reduction in impervious cover in developed areas as a realistic management scenario. As explained earlier this is one of the scenarios included simply as a way of making an observable change in TOTP loading. In some situations reductions are possible, however, and in essentially all situations stormwater management options do exist (i.e. retention ponds) that would result in less direct runoff to streams, thus reducing NPS loading. Some of those options do not result in greater on-site infiltration so to that the results from the model for this scenario may not actually occur.

The principles discussed above have a sound scientific basis, however, and the results do serve to help illustrate the larger point that loading changes are not all equivalent. The above example made the point for NPS loads. In contrast, all reductions in PS loads reduce the downstream effect compared to the prior related scenario, e.g. scenario 10 compared to 7.

Finally, it must be emphasized that for scenario analysis, NPS changes were applied on a watershed-wide basis. The scenarios were developed as a way of making general observations about the effect of certain activities on total phosphorus loading to Fishing Creek Reservoir. Activities that may take place in a specific catchment, or variable application among catchments, is a level of analysis that can be done in the future with this model. Based on the apparent sensitivity of the river to NPS loading changes, it seems unlikely that a single change to one catchment, even a hotspot, will be significantly manifested in Fishing Creek Reservoir. This is not to discourage locating and correcting problem areas because they can have locally and regionally severe effects on water quality. This is only to emphasize the point that Fishing Creek

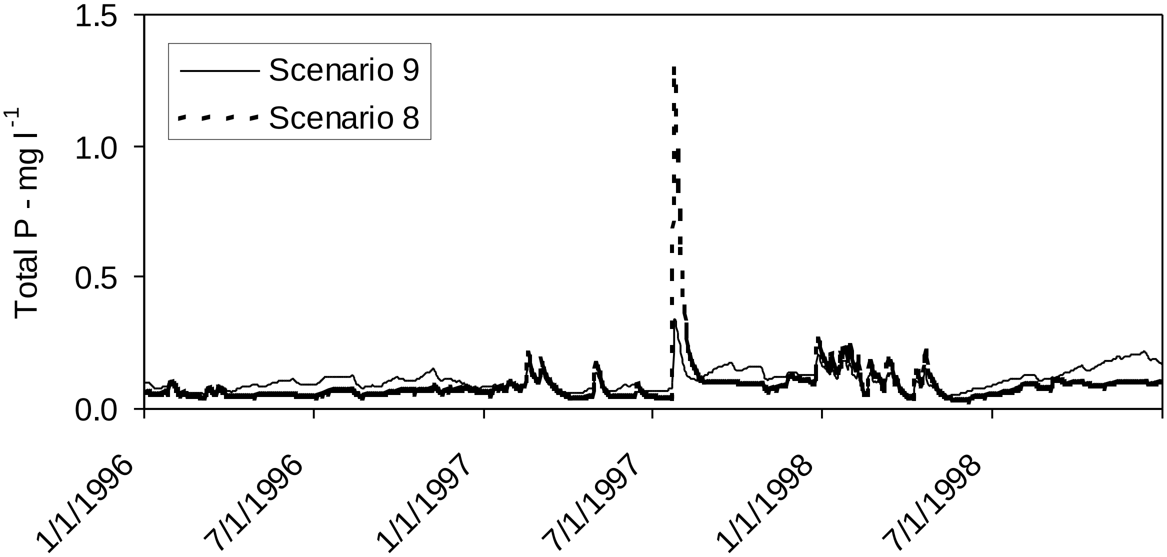


Fig. 22. Comparison of TOTP concentrations in the Catawba River above Fishing Creek Reservoir in two scenarios. Scenario 9 cut urban impervious cover by 50%. See text for discussion.

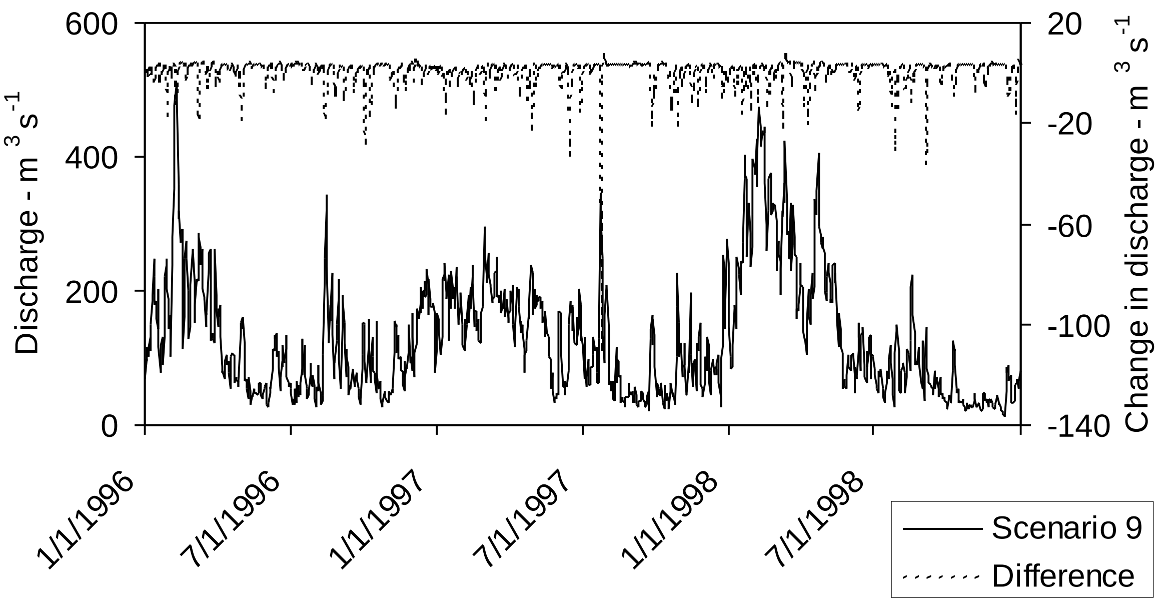


Fig. 23. Simulated discharge of the Catawba River above Fishing Creek Reservoir during scenario 9, and the daily discharge difference from scenario 8. Scenario 9 cut urban impervious cover by 50%. See text for discussion.

Reservoir integrates the effects of activities over a very large area and it receives very large total phosphorus load.

Phosphorus loss

In the WARMF model phosphorus can be in either dissolved or particulate form. It participates in adsorption-desorption equilibrium kinetics and dissolved fractions can also be taken up by biotic processes. In particulate form it can settle in either a river or reservoir. In the river it is subject to resuspension, but this may not occur within the time frame of a modeling exercise, at least not for all the deposited sediment. In actual rivers the downstream transport of a sediment particle can occur over time intervals up to decades and even centuries (Knighton, 1998). Settled particulate material and associated phosphorus in reservoirs is permanently removed from nutrient dynamics in WARMF.

We estimate the effect of the loss processes within our modeling timeframe by introducing a continuous phosphorus point source load at a location well up into the watershed for the entire simulation. We use the CMU WWTP at Sugar Creek as matter of convenience because it is already in the model as a point source. Within the stream reach of the WWTP, the full load exists. As it is tracked downstream, the mass quantity is attenuated (Fig. 24).

In this example, by the time the phosphorus load reaches Fishing Creek Reservoir, 10% has been lost. At the headwaters of Lake Wateree 30% has been lost. We used a phosphorus decrease to develop this relationship, but the relationship is the same for phosphorus regardless of the type of change. A unit change of phosphorus upstream in the watershed does not equate to a unit change in the downstream reservoirs.

Distance from the reservoirs is an important factor. In this example, a 10% loss occurs along 55 km from the Sugar Creek WWTP to Fishing Creek Reservoir. The loss would have been only about 4% if the load had occurred near the confluence of Sugar Creek and the Catawba River, roughly 22 km upstream from Fishing Creek Reservoir. It is worth noting that in this example, 6% of the phosphorus load is lost in the 23 km transport down Sugar Creek and only an additional 4% in the 22 km transport in the Catawba River to Fishing Creek Reservoir. Other studies report greater loss rates in smaller streams, an effect attributed to their larger perimeter-to-volume ratio (Smith et al., 1997).

This example serves to illustrate that watershed management actions that will change phosphorus loading to streams will not be fully manifested in the downstream reservoirs. Although it is relatively straightforward to analytically estimate the effect of this for point sources, for diffuse sources the issue is far more complex. In either case a specific potential management action should be studied with the use of the WARMF model so that uncertainties can be reduced (e.g. the effect of stream size, travel time and distance, and equilibrium kinetics).

A final point from this example is that 20% of the phosphorus load is sequestered in the Fishing Creek-Great Falls-Cedar Creek chain of reservoirs, and an additional 40% in Lake Wateree. This result is qualitatively congruent with will established principles of reservoir limnology (Kennedy

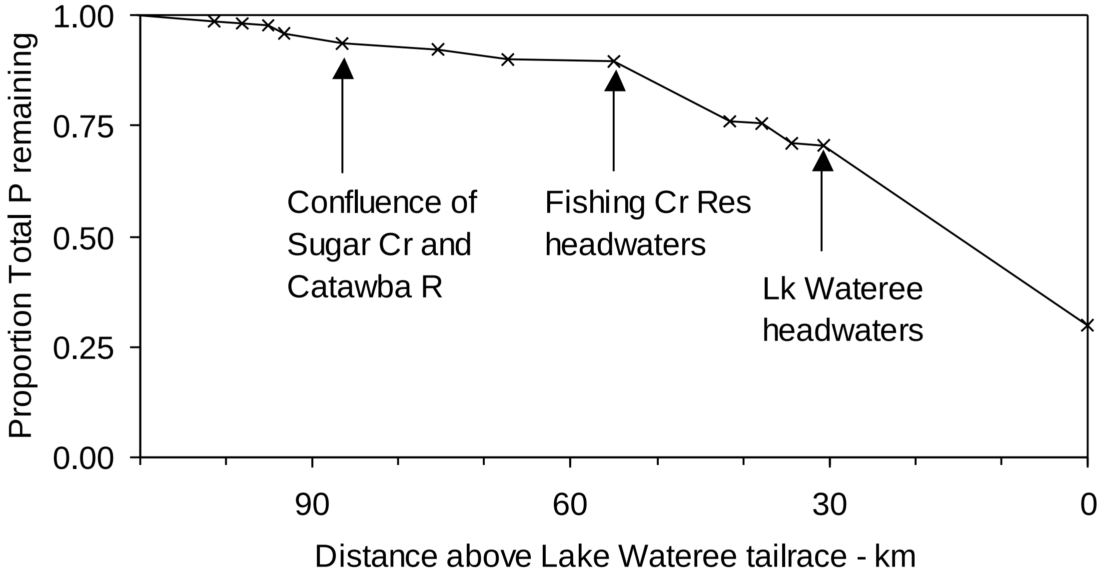


Fig. 24. The effect of biogeochemical loss processes on total phosphorus loading during downstream transport. The proportions are the quantity remaining of a fixed, continuous TOTP load that is introduced at a point 110 km upstream from the Lake Wateree tailrace. See text for discussion.

and Walker, 1990), and it suggests that now after many years of high phosphorus loading to these lower Catawba River reservoirs, a significant amount is stored in the sediment layer. This accumulated stock is frequently a periodic source of phosphorus in the water column first as an equilibrium process by diffusion from the sediment then subsequent turbulent mixing up into the water column (Kennedy and Walker, 1990). Also, several studies report that when external phosphorus loading to a eutrophic lake or reservoir decreases, internal loading from the sediment can take several years to depurate (e.g. Recknagel et al., 1995; Welch and Cooke, 1995).

It is not known if internal loading occurs in these reservoirs. It is reasonable to assume that it does occur, however, given the frequent reporting in the literature and based on other modeling studies of South Carolina reservoirs, including Lake Wateree (Tufford and McKellar, 1999; Tufford et al., 1999). The WARMF model does not simulate this internal loading process. Although we do not know how big the sediment stock of phosphorus is in these reservoirs, or how long it may take the reservoirs to re-equilibrate to new external loading levels, the results of scenarios that include significant reductions in phosphorus loading in the Catawba River should be interpreted as end-effects that may not be immediately observed in the reservoirs. This concern may be somewhat offset by the frequent occurrence that large changes (e.g. large phosphorus reductions) are implemented over a period of a few years. So internal loading equilibration may occur concurrently with a slow transition to a large change in phosphorus loading.

Another implication of the possible occurrence of internal loading in these reservoirs is that it would mean the NPS loading specifications in the model are too large. This would have been needed as a compensation for the absence of a loading source, internal loading, in the WARMF model. The existence of internal loading also could be a partial or total explanation for the seasonal mismatches sometimes seen in the nutrient calibration in the reservoirs (Figs. 10, 11, 14, 16, 17). The forcing functions of internal loading are different than for the other loading sources, so the temporal pattern of its effect in the reservoirs would be different (Kennedy and Walker, 1990; Tufford and McKellar, 1999).

Reservoir phosphorus loading

We focused our attention to watershed nutrient loading on the Catawba River above Fishing Creek Reservoir. According to the calibrated model, the 3-year mean phosphorus load in the Catawba River was 2097 kg d^{-1}. Tributary watersheds and PS loads below Fishing Creek Reservoir brought an additional 137 kg d^{-1} for a total of 2234 kg d^{-1} entering Lake Wateree. Attention to this additional load is warranted given the proportionately greater impact on Lake Wateree (discussed above). For this report, however, there was greater opportunity to demonstrate the use of the model for analysis of watershed and reservoir dynamics, and the effect of change in nutrient loads, by looking at the watershed upstream from Fishing Creek Reservoir.

The scenario analysis and phosphorus loss analysis presented above allows us to estimate the proportionate sources of TOTP loading into Fishing Creek Reservoir. Of the 2097 kg d^{-1} entering the reservoir, approximately 15% was from Lake Wylie outflow, 46% was from point sources, and 39% was from nonpoint sources. Given what the analysis above shows about phosphorus losses over distance and the trapping ability of reservoirs, it follows that a substantial change in loading into Lake Wylie would be needed to effect even a small percentage point change in the phosphorus loading to Fishing Creek Reservoir.

In contrast, both point and nonpoint sources within the lower Catawba River watershed constitute significant proportions of the total phosphorus loading to the lower reservoirs. Point sources are the largest, but not dominant, fraction. Clearly, watershed management activities that focus on PS and NPS loading within the study area will have the greatest effect in reducing the significant excess in phosphorus loading.

A final point on this topic is to point out and explain an apparent discrepancy in this report. Figure 4 indicates 251 kg d^{-1} (554 lb d^{-1}) total phosphorus discharging from Lake Wylie and 1420 kg d^{-1} (3130 lb d^{-1}) entering Lake Wateree. The simulation results from this study show 368 kg d^{-1} and 2234 kg d^{-1}, respectively. The primary explanation for this, as discussed earlier, is that the infrequency of monitoring data (compared to the simulation model) misses most of the peaks in constituent concentration that the model produces. Were the basic relationship between the two load estimates greatly different between the methods of deriving them there would be cause for concern. In this case there is none.

In summary of the scenario analysis, feasible management actions could include reductions in point source discharges (i.e. recent permit reductions for NC and SC, plus an additional 50% reduction in SC point sources) and nonpoint sources (i.e. a 2/3 reduction in fertilizer applications as well as a 10 m vegetated buffer along 90 % of all streams in the basin). The model estimates that the cumulative effect of these scenarios would reduce total phosphorus loading by 40% and would reduce exceedences of the chlorophyll standard in the major reservoirs to < 25%. Although these scenarios would reduce the phosphorus concentrations in the reservoirs, the annual variability would still yield > 25% exceedence of the phosphorus standard. To limit phosphorus exceedences to < 25% would require reducing the total load to < 600 kg/day (representing a 70% reduction from base conditions) and would require additional limits on both point and nonpoint sources.

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APPENDIX A

Base Flow and Storm Flow Patterns of Phosphorus Flux in the Upper Fishing Creek Sub-Basin

Although most of the calibration data were derived from SCDHEC and Duke Energy monitoring stations on the Lower Catawba River and reservoirs, additional information on patterns of phosphorus loading was gained from sampling within the upper Fishing Creek sub-basin. The objectives of this sampling and analyses were to contrast patterns of phosphorus loading between base flow and storm flow conditions in a representative sub-basin of the Lower Catawba. The full scope of the Fishing Creek study was reported by Grose (2001. Nutrient dynamics in the upper Fishing Creek basin: A sub basin within the Lower Catawba River (SC) Watershed. MSPH Thesis, University of South Carolina). (The thesis is in Appendix E.) A component of the Fishing Creek study, reported here, utilized a state-certified laboratory (Duke Energy Analytical Laboratory) for the nutrient analyses and the resulting data were provided to Systech Engineering for use in model calibration.

Methods

Study Site. Upper Fishing Creek extends 33.8 km from the headwaters near the town of York to its confluence with Wildcat Creek (Fig. A1). The sub-basin covers an area of approximately 128 km^2 and includes a diverse mix of land use/land cover types as well as a single point source of municipal wastewater. This sub-basin allowed for examination of the contributions of nonpoint sources and their relationship to the inflow of a major point source discharge. Supporting information on the point source discharge from the town of York (flow and phosphorus load) was derived from monthly Discharge Monitoring Reports (DMRs) as reported to SC DHEC and the US EPA permit compliance system (http://www.epa.gov/enviro/html/pcs/pcs_query_java.html).

Seven sampling locations were chosen to represent the upstream-downstream distributions of phosphorus (Fig. A1, Table A1). Land use/land cover data was based on satellite imagery and 1999 aerial photos (Table A2); sub-watersheds were delineated based on the 7 sampling locations.

Base flow conditions were examined on 9 Aug 2000. At each of the 7 stations, water samples were taken from the center of the stream in acid-cleaned high-density polyethylene (HDPE) bottles. Samples were immediately stored on ice for transport to the laboratory where they were processed for analysis within 8 hours of collection. Samples for total phosphorus (TP) analyses were acidified to pH<2 with concentrated H_2SO_4. Samples for total dissolved phosphorus (TDP) were filtered through pre-rinsed GF/F filters and then acidified with H_2SO_4. Samples for dissolved ortho-phosphorus (oPO4) were filtered but remained un-acidified. All samples were then placed on ice and shipped overnight to the Duke Energy Analytical Laboratory (SCDHEC Lab ID#:99005). Dissolved ortho-phosphate was analyzed within in 48 hrs by the acid-molybdate method (EPA Method 365.1). TP and TDP were analyzed within 28 days by EPA Method 365.1 after acid persulfate digestion. Dissolved organic phosphorus (DOP) was computed as TDP-oPO_4.

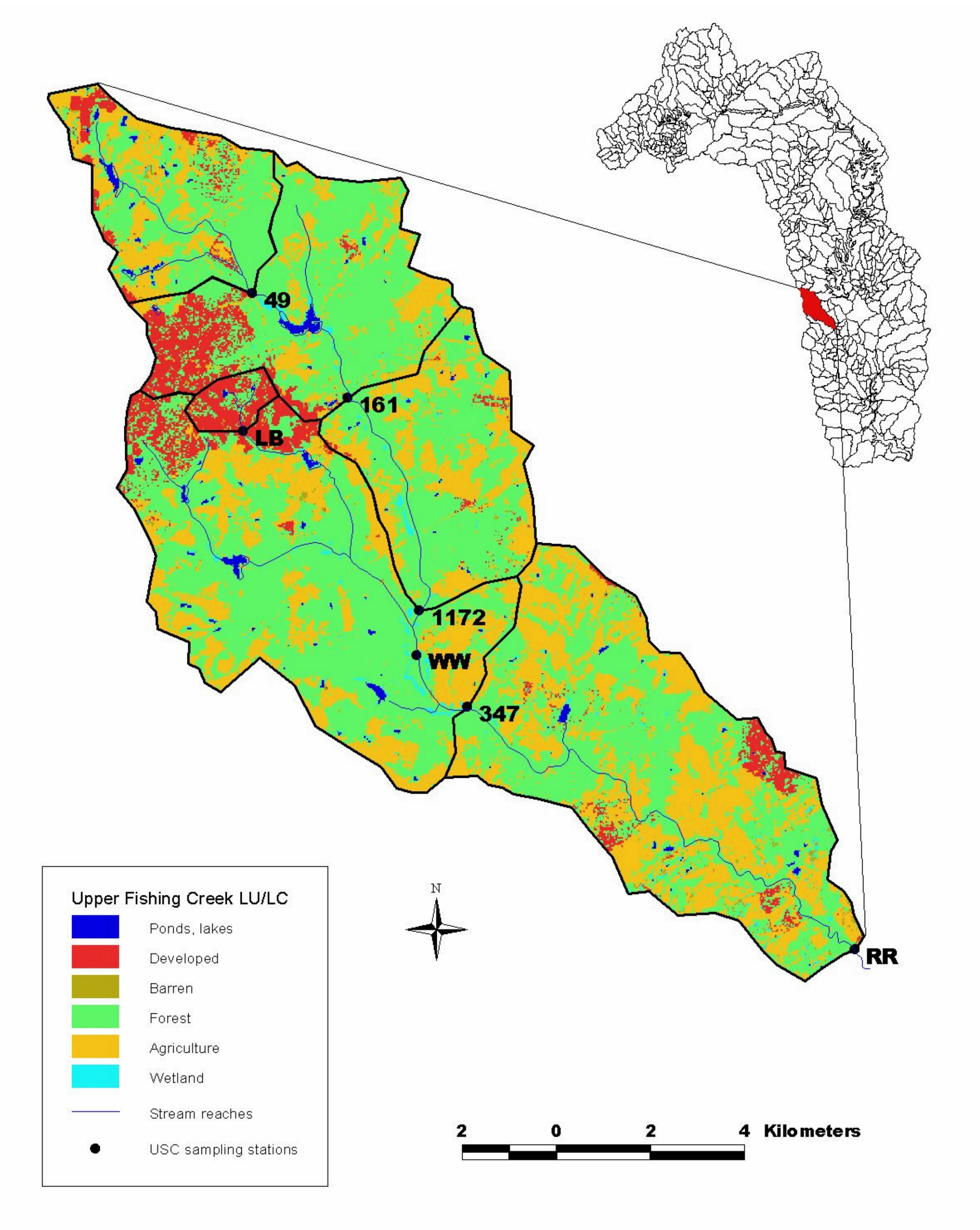

Figure A1. Upper Fishing Creek watershed location with base flow sampling locations and land use/land cover classifications for each sub-watershed.

Table A1. Baseflow sampling station ID's, distance from headwaters, and location information.

Sample ID	River Distance from Headwaters (km)	Location Information
49	4.4	Fishing Creek - Directly upstream from the City of York drinking water reservoir near the headwaters (SC 49)
161	8.2	Fishing Creek - Directly downstream from the drinking water reservoir (SC 161)
1172	13.6	5.4 km downstream from Station 161 (County 1172)
LB	13.9 (Confluence with Fishing Creek)	Langham Branch - City of York (SC 5)
WW	14.8 (Discharge into Fishing Creek)	1.2 km downstream from Station 1172 and 0.9km downstream from the input of Langham Branch into Fishing Creek
347	16.3	Fishing Creek - 1.5 km downstream from wastewater discharge (County 347)
RR	29.4	Fishing Creek - 13.1 km downstream from Station 347 at the Southern Railway trestle (County 998)

Table A2. Land use/land cover proportions in the Upper Fishing Creek sub-basin.

	STATION ID				
	49	161	1172	347	RR
SUB-BASIN AREA (km^2)	13.73	20.57	17.02	37.48	37.67
SUBBASIN PROPORTION					
Water	0.018	0.012	0.003	0.012	0.005
Developed	0.080	0.150	0.014	0.068	0.039
Barren	0.005	0.004	0.005	0.005	0.010
Forest	0.552	0.636	0.616	0.610	0.504
Agriculture	0.340	0.190	0.351	0.295	0.432
Wetland	0.005	0.009	0.010	0.011	0.010

Stream discharge was evaluated at each station by detailed cross-sectional profiles of depth and velocity. Velocity at each cross-sectional position was recorded as the median of 3, 10-sec velocity averages, measured at 0.6 of the total depth using a Marsh-McBirney 2000 electromagnetic flow meter.

Storm Flow Conditions were examined in detail at Station 347 on 8-10 November, 2000. Rainfall was measured by a tipping bucket recorder at the Town of York wastewater treatment plant, approximately 1.5 km upstream from Station 347. Stream hydrography was quantified by recording stream stage (Global WL14X pressure transducer and data logger) every 15 min. throughout the 2-day storm event. Stream discharge (L/s) was then computed using a detailed stage-discharge relationship for Station 347 (Fig. A2).

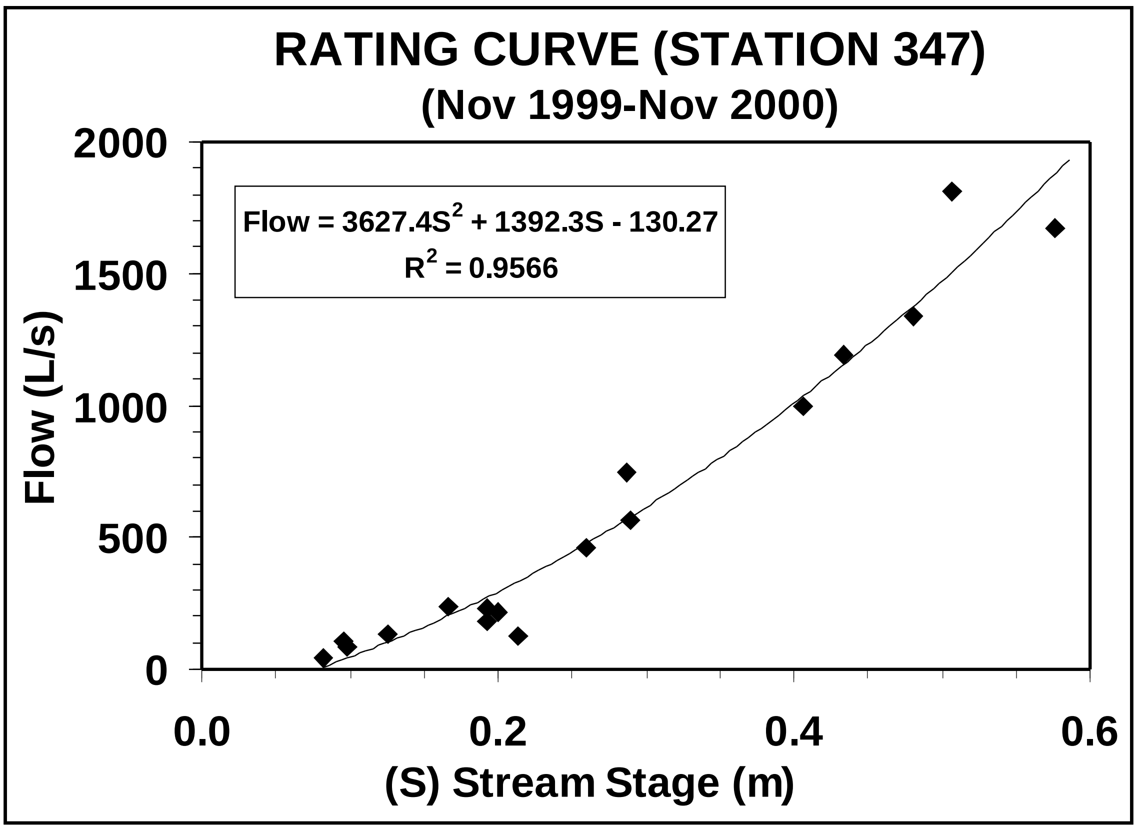

Fig. A2. Stream stage-discharge relationship for Upper Fishing Creek, Station 347. Based on 17 direct measurements of stream stage (S) and stream discharge (computed from depth-velocity profiles), conducted between Nov. 1999 and Nov. 2000.

Temporal changes in phosphorus concentrations during the storm event were examined from a time-series of water samples starting from pre-storm conditions and continuing throughout the storm event. The initial grab sample was taken at 1600 hrs 8

Nov. to document pre-storm conditions while the remaining 13 samples were taken at 1-2 hr intervals by an automated sequential sampler (ISCO-6700). The intake sieve for the water sampler was anchored in the stream channel, 10 cm above stream bottom. The sampler was activated on 9 Nov (1547 hrs) by the initial rise in stream stage (ISCO 1640 water level actuator) and continued sampling every 60 min throughout the rising limb of the storm hydrograph (15:47-20:47, 7 samples). After peak discharge, the sampler was reset to sample at 2-hr intervals throughout the remainder of the sampling period (22:47, Nov 9-10:47 Nov 10, 6 samples). The automated sampler contained ice and melt water to cool samples throughout the sampling event. All samples were transported on ice to the laboratory where they were processes for analysis within four hours of retrieval. As described above for the base flow sampling, the storm flow samples were filtered, preserved, placed on ice and shipped the following day to Duke Analytical Laboratory for analyses.

Results and Discussion

Base Flow Patterns. Base flow in the upper Fishing Creek sub-basin for the dry conditions of August 2000 increased from 15.5 L/s in the headwaters to 136.8 L/s at the downstream boundary of the study area (Fig. A3). Municipal wastewater from the Town of York (31-36 L/s; August and September DMRs) accounted for 65-76% of the increase in stream discharge along the middle reaches of the watershed. The wastewater accounted for 37-44% of the total stream flow (82.1 L/s) at the station immediately downstream from the wastewater treatment discharge (Station 347).

Total phosphorus concentrations in the stream exhibited a pronounced response to the wastewater discharge, increasing from 0.03 mg/L at the 3 stations above the point source, to 0.42 mg/L immediately below the point source (Station 347). Total phosphorus at all stream stations was composed mostly of dissolved oPO_4 (i.e. other forms of phosphorus (particulate and dissolved organics) were below the limits of detection during this low-flow period). The corresponding increase in stream load (2.86 kg/day) between the middle 2 stations was largely accounted for (91%) by the wastewater discharge (2.61 ± 0.83(sd) kg/day mean for Aug. and Sep.). At that point in the stream, the wastewater accounted for 88% of the total phosphorus load. Downstream from the wastewater input, phosphorus concentrations declined 76.2% by a distance of 13.1 km downstream from Station 347.

Over the entire annual cycle of 2000, base flow in upper Fishing Creek exhibited distinct seasonal patterns from lower flows in the summer and fall (< 200 L/s at the mid-point, Station 347), to higher flows during the winter months (800-1200 L/s)(Gross 2001). At the time of our 9 August 2000 base flow sampling, there was a 22.1 inch rainfall deficit since January of the previous year[1] and stream flow was probably well below normal. Phosphorus concentrations and loadings were clearly dominated by the single point source of wastewater discharge although there was considerable decrease in phosphorus concentrations downstream. This decrease due to uptake and sedimentation processes in the stream took place over the 13.1 km distance between the last 2 stations

[1] Southeastern Regional Climate Center; data for Winthrop University, approx. 13 km southeast of the mid section of Upper Fishing Creek; http://www.dnr.state.sc.us/climate/sercc/)

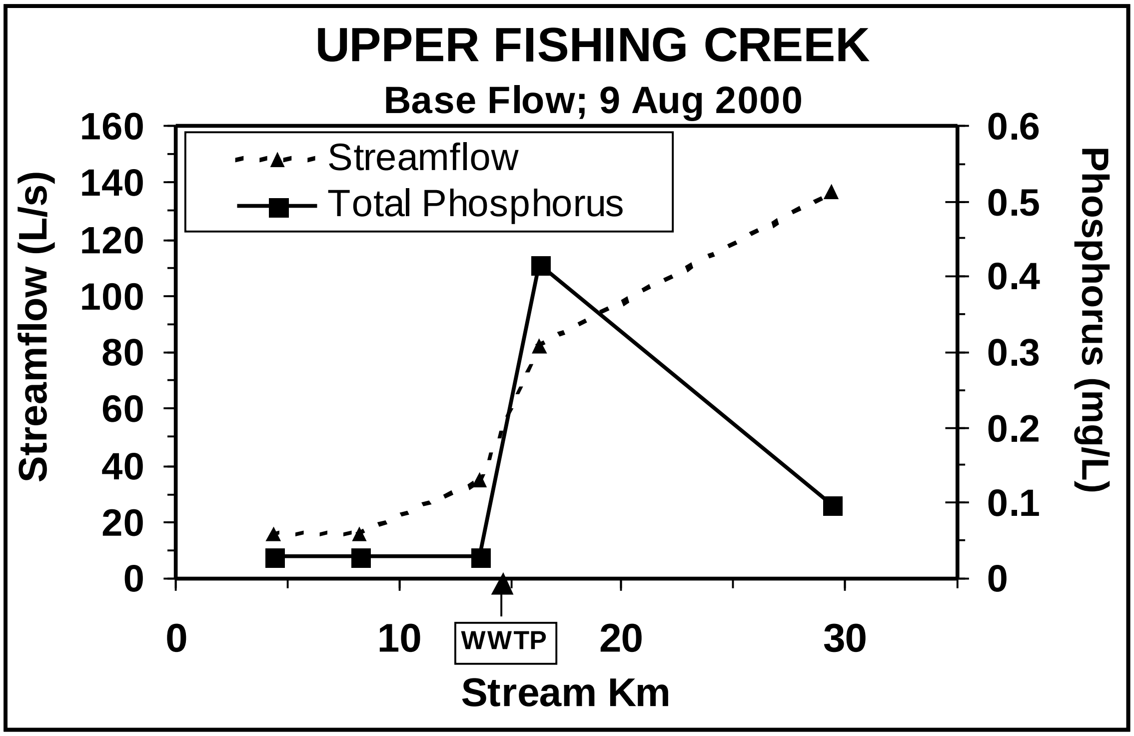

Fig. A3. Stream flow and total phosphorus distributions along upper Fishing Creek during base flow conditions, 9 Aug. 2000.

Based the velocity profiles at the last 2 stations, the mean velocity was 0.03 m/s and the estimated time-of-travel between the stations would be 5.05 days. This loss of total phosphorus corresponded to a first-order "decay" rate of approximately 28% day^{-1} during these low-flow conditions. During higher discharges, especially those associated with storm events, the loss rates would be considerably less due to increased nonpoint source loading as well as sediment resuspension in the stream channel associated with higher stream velocities.

Storm Flow Patterns. By 8 November (2000), base flow at Station 347 had increased from 82 L/s during August to approximately 300 L/s (Fig. A4). Although traces of rain fell (.02 in) on 8 Nov., the first wave of intense precipitation occurred the on 9 Nov. (7:00-8:30 AM). The rising limb of the storm hydrograph exhibited an approximate 2-fold increase in stream discharge to a peak of 627 L/s by 9:45 PM, about 12 hours after the rain event. A second wave of precipitation occurred just after peak discharge (9:45-10:00 PM), causing secondary peaks in stream discharge the following day (10 Nov.).

Prior the storm event, total phosphorus in the stream (0.29 mg/L) was an order a magnitude higher than during August base flow conditions, owing in part to a higher level of base flow and potentially higher inputs from nonpoint sources. The phosphorus loading from the wastewater discharge (2.0 kg/da, Oct-Dec DMRs) accounted for only 23% of the pre-storm total phosphorus loading at Station 347 (8.8 kg/d) in contrast to the 88% contribution to stream loading during the August low flow conditions. However, similar to the August base flow conditions, pre-storm total phosphorus in the stream in November was dominated by dissolved oPO4 (89%) with relatively low levels of DOP (5%).

During the rising limb of the storm hydrograph, total phosphorus concentration increased by 76 %, reaching a peak of 0.5 mg/L, well before the peak of stream discharge (Fig. A4). This rise in total phosphorus corresponded, in part, to peaks in DOP. Starting from a concentration near the lower limit of detection (0.02 mg/L), DOP increased by > 10-fold during the rising limb of the hydrograph, reaching a peak of 0.27 mg/L, coincident with the TP peak. DOP dynamics during the storm suggested an initial nonpoint source input of soluble organic matter associated with first stages of storm flow. In contrast, dissolved oPO_4 concentrations remained relatively stable during the rising limb (0.2-0.3 mg/L), exhibiting a steady decline after peak discharge. Even though oPO_4 did not exhibit major peaks during the rising limb, the corresponding increase in oPO_4 loading with the rise in stream discharge suggested a considerable nonpoint source of oPO_4 runoff associated with the first stages of the storm event. All forms of phosphorus (TP, DOP, and oPO4) declined after peak discharge, suggesting some dilution after the initial phase of the storm event.

Integrating the total phosphorus transport through the storm event (3:47 PM 9 Nov through 10:47 AM 10 Nov) yielded 18.7 kg/d of phosphorus transport. Assuming a 2 kg/d load from the wastewater discharge (based on Oct.-Dec. DMRs), the wastewater accounted for only 11% of the phosphorus load during the storm event. Clearly, the stream load during this moderate storm even was dominated (89%) by nonpoint sources of phosphorus runoff. Sixty percent of the total phosphorus load was oPO4 and 33% was DOP. The estimated 16.7 kg/d contribution of nonpoint source runoff from the cumulative watershed area drained by Station 347 (90.6 km^2, Table A2) corresponded to a 0.18 kg km^{-2} da^{-1} of nonpoint source phosphorus load associated with a moderate storm event.

In summary, it is instructive to compare point source and nonpoint source contributions to stream phosphorus loads for three distinct hydrologic conditions (low base flow, higher base flow, and storm flow). During low, base flow conditions of late summer (9 Aug., 2000,), stream phosphorus transport at Station 347, just downstream from a major point source of wastewater discharge (Town of York,) was dominated by the wastewater (88%) with a relatively low contribution from nonpoint sources of runoff (12%). By autumn (8 Nov., 2000,) base flow was almost 4 times higher than in Aug; total phosphorus transport in the stream showed considerable influence from nonpoint sources (77%). Although the absolute point source discharge was similar (2-3 kg/da), its relative contribution during the elevated base flow was considerable less (23%) than during low base flow conditions. During the moderate storm event of 9-10 Nov (0.4 inches of rain in 24 hours), total phosphorus transport in the stream became largely dominated by nonpoint sources (89%), suggesting considerable nonpoint source loading throughout the basin. These data were used to help calibrate the WARMF model, which was designed to simulate the complex interactions among land use, hydrology, nonpoint runoff, point source discharges, and water quality dynamics throughout the Lower Catawba Basin.

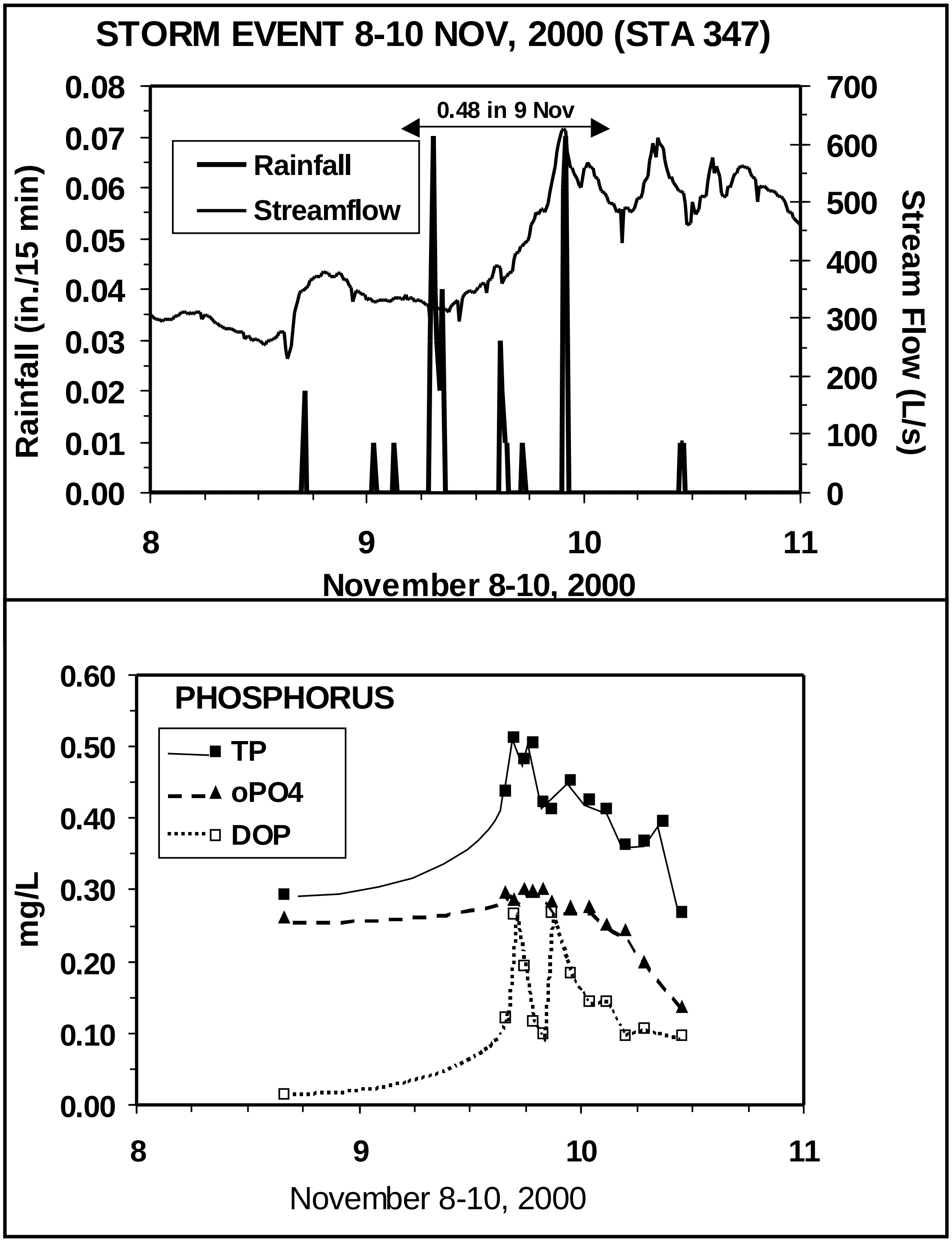

Fig. A4. Storm flow patterns of precipitation, stream discharge and phosphorus concentration at station 347 on 8-10 November 2000.

APPENDIX C

Responses to stakeholder comments

During this project we held several stakeholder meetings (see below). During these meetings we solicited comments about any aspect of the project. We received two sets of formal comments relating to the modeling aspect of the project. One set was included in a letter from the Catawba River TMDL Coalition (CRTC) sent to Kathy Stecker (SCDHEC) on 16 September 2002. The second set was contained in an e-mail from Dr. Joseph DePinto (Limno-Tech, Inc.) on 05 March 2003 as follow-up to a modeling review meeting held 03 February 2003 in Charlotte.

A large proportion, roughly half, of the comments in the CRTC letter were issues for SCDHEC to respond to. Of the modeling related comments, many were repeated or were similar to comments in the DePinto e-mail. The prior sections of this final report directly address the majority of the comments. Here we will provide some additional response as an aid in understanding our work.

Data quality – The water quality data used to calibrate and verify the model represented field and laboratory analysis by SCDHEC, NCDENR, Mecklenburg County, and Duke Energy. The stream discharge data are from USGS gaging stations. We acknowledge that one approach to evaluation of field data includes looking for outliers or other potentially anomalous values. With the relative paucity of field data, however, particularly in the target reservoir segments, we chose to use all data. Our calibration and verification method of fitting quarterly means suppresses the influence of one or a few anomalous values of field data.

WARMF model development – The development and calibration of the model was accomplished primarily by Systech Engineering. Details of their work can be found in Appendix B. Our additional calibration, as described earlier, focused on (1) increasing the NPS nutrient loading by increased fertilization and reduced riparian buffers, and (2) improving the fit of CHLa in the reservoirs by altering phytoplankton community parameters for growth rate and temperature. The NPS loading changes were based on information available from the USDA, Clemson University, and discussions with Systech Engineering. The phytoplankton growth parameters are within well established ranges found in the modeling literature.

The final calibration and verification intervals were selected based on the availability of observed values in key reservoir segments. This consideration superceded all others, including meteorology and hydrology. We used statistical tests commonly found in the modeling literature. Our general approach was to use quarterly means for comparison of fit rather than daily values. This gave us the ability to estimate variability in the observed data yet it left broad seasonal trends intact. It also restricted the time frames we could use for calibration and verification to those with at least two observed values during a calendar quarter. We believe this restriction was offset by the greater information available in the statistical moments versus individual daily values. It also provides part of the basis for a more through error analysis, which we agree is a good idea but we did not do because of time constraints.

Wetlands – This is a description from Systech: “We account for upland wetlands using the 'wetland' land use. The characteristics of this land use are specified in the system coefficient dialog; the crop factor for wetlands is set to zero so that no soil erosion occurs, and the productivity is relatively high so that nutrients are taken up, etc. Riparian wetlands are specified as buffer strips; slope, width and percent buffered can be set to control the amount of sediment and phosphorus in overland flow that is removed before entering the stream.”

A riparian wetland component with additional biogeochemical processes is currently under development for WARMF. It should be noted, however, that steam-side wetlands along the small and medium sized streams of the South Carolina Piedmont are uncommon and generally not of great extent when they do occur. There are geomorphological reasons for this that also suggest widespread use of constructed riparian wetlands may not be a feasible management strategy for controlling NPS loading. Thus it is problematic as to whether or not a more physically-based wetland component in WARMF would significantly change our results or be especially useful for scenario analysis in this study area.

Model application – One of our primary interests was to use the calibrated model to derive information of use in assessing the possible effect of changes in phosphorus loading to the study area streams and reservoirs. We did this in two ways; scenario analysis and exceedence charts. The scenario results were used to create the exceedence charts. For the scenario analysis we ran a combination of scenarios, some of which reflect already planned management actions. Other scenarios are possibly feasible, others not, but the suite of them provides a large range of phosphorus loading and reservoir response. The primary conclusions from these are that (1) the reservoirs receive a phosphorus load greatly in excess of what they can accept and be within compliance, and (2) the effect of various management actions are not unit equivalent but are dependent upon distance from the reservoirs and whether or not it is a PS or NPS targeted action. These are discussed in greater detail in earlier sections of this report.

Listing of Stakeholder Meeting Participation

May 3 1999: Presented TMDL study plan to a general stakeholder meeting convened by DHEC; Catawba Regional Council of Government, Rock Hill;

Oct 13 1999 Presented TMDL study plan at stakeholder meeting and goal setting workshop convened by DHEC ; Catawba Regional Council of Government, Rock Hill

Oct 19 1999: ; Presented TMDL study plan at stakeholder meeting and goal-setting workshop convened by DHEC, Camden.

May 5 2000 Attended meeting and participated in discusions of the Bi-State Catawba River Task Force, Catawba Regional Wastewater Committee (Environ. Sub-Committee); Catawba Council of Government, Rock Hill.

Feb 22, 2001: Presented preliminary results of NPS sampling and TMDL analysis SC Catawba River Task Force; Rock Hill.

Mar 7, 2001: Presented preliminary results of NPS sampling and TMDL analysis at the 3rd Annual SC NPS Conference in Columbia

May 23, 2001: Attended meeting and announced TMDL study plan at Bi-State Catawba River Task Force, Andrew Jackson State Park.

May 31, 2001 Presented overview of progress and planned activities for TMDL study to Public Works, City of York:

Feb. 27, 2002 : Presented update of TMDL analysis at the BiState Catawba River Task Force Meeting, Huntersville, NC.

Mar 19, 2002. Nutrient TMDL development for the lower Catawba River watershed. Presentation at the Southeastern Lakes Management Conf., Winston Salem, NC.

May 31, 2002. TMDL Modeling Workshop sponsored by UNC-Charlotte (Dr. James Bowen and Duke Energy (Larry Olmsted). Attended the workshop and discussed model applications with key Catawba stakeholders.

July 31, 2002. Stakeholder meeting for nutrient TMDL on the Catawba. at UNC Charlotte. Presented a detailed analysis of basic model structure and output related to TMDL development. SC DHEC moderated subsequent discussions and stakeholder suggestions

Feb 3, 2003. WARMF model review and analysis. Presented the latest model revisions and output. Joe Depinto (consultant for the Catawba TMDL Coalition) and Jim Bowen (Engineering professor at UNCC), Tim Wool (USEPA), Wayne Harden (SCDHEC), and Rodney Wilson (SCDHEC) provided external comment and suggestions.

September 16, 2002

Ms. Kathy Stecker
South Carolina Department of Health and
Environmental Control
P.O. Box 100
Fort Lawn, South Carolina 29714

Catawba River

Dear Ms. Stecker:

The Catawba River TMDL Coalition* would like to express its appreciation for the opportunity to participate at the Catawba River Stakeholders' meeting on July 31. The Coalition recently formed with the objective of protecting the water quality of the Catawba River through a TMDL process driven by sound science and cost-effective and practical decision-making. Based on the July 31 meeting, it appears that the other stakeholders share the Coalition's objectives.

One way the Coalition proposes to assist in the TMDL effort is to offer technical expertise. Towards that end, we are delighted to make available Dr. Joe DePinto to offer support during further development and refinement of the WARMF model. As you know, Dr. DePinto is a renowned modeling expert with a particular specialization in addressing nutrient-impaired waters. He will be a tremendous asset in the process. Dr. DePinto will make coordination plans with Drs. McKellar, Tufford, and Bowen, as discussed at the July 31 meeting.

In the interest of facilitating a scientifically sound TMDL process, we have provided two attachments to this letter. The first reiterates several questions and concerns with regard to the WARMF model. The second attachment offers some simulation options we propose you undertake when the model is adequately developed for that purpose.

Incidentally, we encourage DHEC (perhaps in conjunction with DENR) to consider EPA's Watershed Initiative: Call for Nominations, which you probably saw in the August 20, 2002 *Federal Register*. 67 Fed. Reg. 53,925. The grant funds EPA is offering could provide additional support to the States' efforts to control the substantial nonpoint source loadings to the Catawba River (see our Simulation Recommendations regarding nonpoint source reductions in Attachment 2). Please let us know if there is anything we can do to assist you in pursuing this valuable opportunity.

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* The Coalition currently is comprised of Bowater Incorporated, Celanese Acetate LLC, City of Rock Hill, Duke-Energy Corporation, and Springs Industries Inc.

The Coalition looks forward to continued cooperation with DHEC and the other stakeholders. Please feel free to contact any one of us should you have questions.

Sincerely,

Dale L. Herendeen / RRB

Dale L. Herendeen
Bowater Incorporated
(803) 981-8009

Danny R. McCaskill / RRB

Danny R. McCaskill
Celanese Acetate LLC
(803) 325-6390

Nick W. Stegall / RRB

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George T. Everett / RRB

George T. Everett
Duke-Energy Corporation
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L. A. Graham
Springs Industries Inc.
(803) 547-1737

Attachments

cc: Ms. Sally Knowles
Ms. Michele Woolfolk
Mr. Michael Vead
Dr. Hank McKellar
Dr. Dan Tufford ✓
Dr. Jim Bowen
Dr. Joe DePinto

Attachment 1
Questions and Concerns Regarding WARMF Model

1. Water Quality Target

At the Stakeholders' meeting, DHEC representatives described the process used for setting the State's phosphorus and chlorophyll *a* water quality criteria. We are interested in additional details and would appreciate if you could send us a written description of the process you used.

2. Data Quality

Data quality is an essential consideration in the TMDL process. No matter how reliable the model, sound water quality decisions can be made only if there is a high level of confidence in the data on which the model and the TMDL process will be grounded.

The Coalition urges DHEC to establish and use an appropriate quality assurance program in developing the Catawba River TMDL. That program should begin with preparation of a Quality Assurance Project Plan ("QAPP") specifying a threshold for determining which monitoring data are sufficiently reliable to be used in the TMDL process. The threshold should be demanding, given the significant regulatory consequences that will flow from the Catawba River TMDL.

We understand that DHEC possesses Catawba River monitoring data collected by several different entities over the course of several years. Those data should be reviewed carefully. Some of the data points may not be reliable, and could interfere with model calibration and validation efforts. Data deficiencies may exist even if the analyses were performed by a state certified laboratory as DHEC asserted at the July 31 meeting. Just because a laboratory has been certified on a particular date does not mean it will perform all subsequent testing in accordance with mandatory QA/QC and other protocols, or that the QA/QC results will confirm that the laboratory was in control at the time it was running samples.

The QAPP should establish a data review process for determining which of the available monitoring data, and any new data, are suitable. EPA recently has issued extensive guidance describing and emphasizing the importance of data quality assurance.[1] We encourage DHEC to follow EPA's recommendations so as to ensure the integrity of the TMDL process.

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[1] The following guidance and requirements are examples: *Guidance for Data Quality Assessment* (July 2000); *Guidance for the Data Quality Objectives Process* (August 2000); *Guidance for Preparing Standard Operating Procedures (SOPs)* (March 2001); *EPA Requirements for Quality Management Plans* (March 2001); and *EPA Requirements for Quality Assurance Project Plans* (March 2001).

3. WARMF Model Development

The WARMF modeling framework has the potential to serve as a valuable tool in developing an appropriate TMDL for the Catawba River. All of the many participants responsible for its evolution to this point should be praised for their admirable efforts in shaping the WARMF tool for application to this complex waterbody. Before it is applied to simulate various conditions and ultimately to establish a TMDL with allocations, however, further development is warranted.

The level of effort used to develop a model should reflect the significance of the regulatory consequences that will flow from its application. We recognize that the modeling analysis effort is often limited by the time and resources available, ultimately requiring a judgment on the level of effort and model complexity. For the Catawba River system, however, the consequences of decisions made with WARMF results could be considerable. Furthermore, unreasonable court deadlines do appear to be a limiting factor in completing this TMDL process. As such, a substantial level of effort clearly is warranted. The Coalition recommends that DHEC develop a QAPP to guide further model development. EPA also requires that a QAPP be prepared for model applications to be used in the regulatory process. Draft guidelines for such a modeling QAPP are available in an EPA report.[2] DHEC should consider requesting the WARMF modeling team to prepare such a QAPP; this process guarantees that an appropriate model calibration, application and documentation process is followed and that data used for this process meet defined criteria.

Model development, according to EPA guidance, essentially involves three (3) steps. The process begins with "calibration," which is a process intended to adjust model kinetic parameters in a manner that will minimize the difference between system observed data and model simulated results during the period of observation. Once a model has been calibrated to a set of observed data, but before the model can be used with confidence to make forecasts of the system response to management actions, it is appropriate to "confirm" the model by applying it to simulate an independent set of observed data. Preferably, those data should be collected under a different set of system forcing conditions (*i.e.*, loads, hydrology, meteorology), without changing any of the calibration kinetic parameters. If these new model simulations match the new data within acceptable tolerances, then one can say that the model has been "confirmed" as a useful management tool. If, however, the confirmation comparison is not successful, then the model must be analyzed to determine possible reasons for the discrepancy(s) and model refinements should be made as necessary.

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[2] U.S. Environmental Protection Agency. 2002. *Guidance for Quality Assurance Project Plans for Modeling*. EPA QA/G-5M, Peer Review Draft, Office of Environmental Information, U.S. EPA, Washington, DC.

The final process involves error analysis. Models can only "forecast" how water quality will respond to various loadings under different environmental conditions. There will always be uncertainty associated with those predictions. Decision makers and stakeholders need to know how much uncertainty is at issue, and that is what an error analysis can provide. In its report to Congress on the TMDL process, the National Research Council underscored the importance of error analysis in performing TMDL work.[3]

Following are some comments regarding what remains to be done regarding the configuration, calibration, confirmation, and performance of error analysis of the WARMF model with respect to the Catawba River system. With regard to configuration of the model, one wants to make sure that the model spatial segmentation is consistent with the spatial gradients that exist in the system. The model segmentation should also be consistent with the scale at which the management questions are being addressed. For example, if an embayment on Lake Wateree behaves differently than the main channel of the reservoir, yet it is desirable for that embayment to meet the same water quality standards as elsewhere, then it may be necessary to create a separate model segment representing that embayment. Another example, involves the assessment of whether there are physical, chemical, or biological processes operating in the system that are important to the decisions being made but are not included in the model. Attached algal growth effects on nutrient cycling or nutrient trapping in wetlands are examples of potential model configuration issues for this system.

With regard to calibration and confirmation, the most important thing is to assess whether the available data for these two important steps in modeling are sufficient and consistent with the spatial, temporal, and kinetic complexity of the WARMF model. If not, additional data collection may be warranted. Often the biggest problem with regard to data sufficiency is the availability of accurate loading and source data collected over the same time period and scale as the system response data used to calibrate or confirm the model. Of the available data for calibration and confirmation, one must identify *a priori* which data will be used for calibration and which will be used for the confirmation process. Another important step in calibration is the development of a calibration strategy that involves identification of the overall approach and coefficients that may be adjusted in affecting the calibration. A good sensitivity analysis is very valuable in establishing and justifying the calibration strategy. Finally, a thorough error analysis should be conducted in order to provide decision makers with uncertainty information to guide their decisions. The plan for conducting this whole process is part of the modeling QAPP; and we recommend that the WARMF modeling team develop and implement this plan prior to model application in the TMDL process.

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[3] *Assessing the TMDL Approach to Water Quality Management* (Committee to Assess the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction, National Research Council, June 2001).

4. Nonpoint Source Assessment and Contribution

To date, most of the work associated with the TMDL development process has focused on the relationship between point source phosphorus loadings and ambient phosphorus and chlorophyll *a* levels. The Coalition understands that Professors McKellar and Tufford, funded by a § 319 grant, also plan to address the nonpoint source component of the watershed system.

In the event DHEC concludes that phosphorus load reductions, beyond those already imposed on point sources in North and South Carolina, will be necessary to achieve water quality standards, the Coalition urges the Department to consider nonpoint source reduction options. We recognize that nonpoint source controls generally are not as convenient to identify and achieve as reductions from point sources. We also recognize, however, that reductions from nonpoint sources often can be achieved in a manner that avoids or minimizes the economic hardship that communities and businesses along the Catawba River otherwise might face if additional point source controls were imposed. The Catawba River TMDL process offers DHEC an opportunity to comprehensively evaluate nonpoint source loading reduction options.

Towards that end, the Coalition has two general recommendations. First, we support DHEC's decision to perform an assessment of the phosphorus loading reduction potential from nonpoint sources. We envision that such an effort would entail steps such as:

(1) identifying, within the watershed, all land uses that contribute phosphorus to the Catawba River;

(2) identifying those particular land uses for which best management practices or other nonpoint source controls are technically feasible to effectuate loading reductions;

(3) estimating the load reductions that are deemed to be technically feasible. Those load reduction estimates will be essential for performing simulations and making allocation decisions; and

The second general recommendation regarding nonpoint sources is for DHEC to give adequate consideration to the substantial nonpoint source component originating from North Carolina. To date, the phosphorus loading in the Lake Wylie tailrace attributable to nonpoint sources has been assumed as background. The Coalition urges DHEC not to assume that such background is irreducible. As part of the TMDL process, DHEC shoulc coordinate with DENR to explore opportunities for achieving reductions.

5. Critical Conditions and Water Quality Targets

Once the WARMF model is deemed ready for management application, our understanding is that DHEC will use it to simulate the effect of a variety of input conditions on ambient water quality (particularly phosphorus and chlorophyll *a*) at various locations within the Catawba River system. The ultimate question is what amount of phosphorus load reductions from which sources is necessary and appropriate to achieve water quality standards for nutrients and resulting chlorophyll a in the Catawba River. A key issue in that analysis is under what set of conditions (i.e., "critical conditions"), such as flow, wet weather situations, temporal and spatial averaging ranges, and percent exceedance allowed, should DHEC evaluate compliance with water quality standards?

Flow variations, either by precipitation-runoff events or by hydrologic controls via dam operations can significantly affect the relative contributions of point source and nonpoint source loads and the resulting phosphorus and chlorophyll a concentrations in the river. For example, high flows resulting from wet weather events will contribute more NPS phosphorus loads to the system and, thus, be responsible for increases in TP levels. On the other hand, low flow, high temperature conditions will provide more opportunity for algal growth in lakes because of longer hydraulic retention times. Therefore, great care must be taken in selection of flow conditions that are input to the model during system TMDL calculations.

Another decision that must be made is the spatial area and temporal period over which model results will be averaged in order to establish water quality targets in the TMDL. One thing that must be recognized is that the model output and hence the averaging resolution is limited by the size of model segments (cannot get finer resolution than a single completely-mixed model segment) and the time scale of the model outputs (daily in the current WARMF model). In many cases, however, it makes sense to consider averaging over multiple segments that are part of the same reach of the river or the same lake. That may or may not be appropriate for the Catawba River System.

Also, because of the complete-mix assumption for model segments and the uncertainty of watershed runoff time lags, it may be that the model will predict rapid increases in concentrations that really do not occur in the system. In addition, there often is a threshold time period, which must be exceeded before a significant system response will be seen (chlorophyll a is a good example). All this is to say that great care must be taken in selection of averaging scales (both time and space) for setting targets for listed parameters and assessing model simulations with those targets. For example, it might make more sense to average phosphorus and chlorophyll a over a month or season rather than simply look at model simulations on a daily basis.

Finally, we want to note that DHEC, in determining 303(d) listings for 2002, deemed water quality standard excursions in less than 25% of the samples to be in compliance with the criteria. To quote the listing document, "For...waters with total numeric phosphorus, total nitrogen, and/or chlorophyll a criteria, if the appropriate criterion is exceeded in more than 25% of the samples, the criterion is not supported..." Given that DHEC has established, and EPA has approved, a method by which to assess compliance with South Carolina's nutrient criteria, that method should be used in the TMDL analysis.

6. Wet Weather v. Dry Weather TMDL

At the July 31 Stakeholders' meeting, Dr. McKellar noted that ambient phosphorus measurements were elevated following storm events. That observation should be considered carefully in developing the TMDL. TMDLs are expected to address water quality standards attainment under both wet and dry weather conditions. The phosphorus load reductions that may need to be imposed on point and/or nonpoint sources likely will differ depending on wet and dry weather conditions.

Because phosphorus levels apparently are elevated after storm events, and because point source phosphorus loadings generally are unaffected by storm events, the elevated phosphorus measurements (above dry weather measurements) likely are attributable to nonpoint source loadings. Thus, storm-related ambient phosphorus levels, if in excess of the TMDL target for phosphorus, would need to be reduced through nonpoint source loading reductions. Point source load reductions are not going to be effective at reducing those incremental phosphorus levels. Any load reductions imposed on point sources should be imposed only to the extent necessary, in combination with nonpoint source load reductions, to reduce any excess ambient phosphorus levels attributable to loadings during under dry weather conditions.

Of course the Coalition recognizes that DHEC also plans to use chlorophyll *a* as a TMDL target, and that it will consider that target, along with phosphorus, in developing allocations.

7. Localized Loadings

In developing a TMDL for the Catawba River, the goal will be to achieve and maintain water quality throughout the waterbody. In pursuing that goal, it is essential to develop an understanding of how the "location" of phosphorus loading sources can be expected to influence water quality.

For example, if elevated phosphorus and/or chlorophyll *a* measurements in an embayment are attributable primarily to phosphorus loadings flowing from land uses contiguous to the embayment, as opposed to loadings originating from regional upstream sources, a TMDL that focuses just on regional phosphorus loadings could result in phosphorus load reductions burdens that are: (1) more onerous than necessary to achieve water quality standards in most of the waterbody, and (2) ineffective in achieving water quality standards in segments of the waterbody influenced primarily by local loadings.

DHEC should identify and properly address any such localized areas in the TMDL process.

8. Wetlands

The influence of wetlands on nutrient dynamics should be considered in the modeling effort. Wetlands often act as nutrient traps, preventing nutrient runoff from entering a receiving waterbody. WARMF currently does not have a separate sub-model for computing the nutrient dynamics in wetlands within a watershed. However, it may be possible to "simulate" the effects of wetlands in riparian zones by adjusting riparian buffer coefficients in the model. The modeling team should investigate the potential importance of wetlands in this system and how it may be handled in the WARMF modeling framework.

Attachment 2
Simulation Recommendations

Once the modeling expert panel (discussed at the July 31 Stakeholders' meeting) has concluded that the model is adequately developed for management decision application, the Coalition recommends that the following simulations be performed. The Coalition views this as an iterative process. Additional simulations will be necessary once the technically feasible nonpoint source load reduction amounts have been calculated, and DHEC has other sufficient information with which to make allocation decisions for the TMDL process.

1. Assume achievement of the point source load reductions required in existing NPDES permits, and simulate the effect on phosphorus and chlorophyll *a* levels of reducing overall nonpoint source loadings by 100%, 50%, and 25%.

2. If the simulation in number 1 predicts unacceptable phosphorus and/or chlorophyll *a* levels at any of the nonpoint source loading reduction percentages, simulate the total point source load reduction (expressed in pounds per an appropriate time period) beyond existing NPDES limits that will be necessary for each nonpoint source loading percentage assumption.

3. Divide the Catawba River system into segments that separately contain the lakes and any river stretches deemed by DHEC to be impaired by nutrients. For each segment of the Catawba River for which the model predicts water quality standards excursions even after achievement of point source load reductions required in existing NPDES permits, simulate the effect on each segment of reducing nonpoint source phosphorus loadings by 100%, 50%, and 25%, from just the loads flowing into each respective segment from adjacent land uses.

Draft Summary of WARMF Model Review
February 3, 2003; UNC-Charlotte

Participants:

Jim Bowen, Engineering (UNCC), Joe DePinto (LimnoTech), Wayne Harden (SCDHEC), Hank McKellar (USC), Dan Tufford (USC), Rodney Wilson (SCDHEC), Tim Wool (US EPA)

Calibration:

At the current stage of development, the model under-predicts phosphorus in both Fishing Creek Reservoir and Lake Wateree; it over-predicts chlorophyll-a in Fishing Creek Reservoir. Addressing these issues may require Systech's modification of the model to allow lake-specific variations in algal growth coefficients.

Further calibration efforts should focus on the following:

- Refining point-source estimates for both phosphorus and nitrogen. Although limited monitoring data exist for nitrogen point sources; estimates should be included to refine nutrient-algal interactions in the model. Although limited monitoring data exist for both N and P concentrations in some point sources (i.e. cooling water discharges), concentration estimates should be included (i.e. at least ambient levels) to improve mass-balances in the model.
- Trace nutrient deficits upstream from Fishing Creek to help identify the source of mass-balance discrepancies. Focus on Sugar Creek, the dominant source of nutrients to the Catawba
- Search for site-specific data on soil nutrient concentrations and related adsorption/partition coefficients to improve nonpoint source loading estimates.

Verification:

- Verify model results by comparing output with pre-1995 monitoring data.
- Use the uncertainty in verification analysis to derive the "margin of safety" in TMDL limits.
- Alternatively, use the results of the verification testing to further refine the calibration to account for a greater range of conditions.

TMDL Targets/Analyses

- The group recommended that TMDL target(s) for this work should focus both on total phosphorus (0.06 mg/l) and chlorophyll-a (40 µg/l) in Fishing Creek Reservoir and Lake Wateree. While calibration tests will be focused on seasonal variability and means, TMDL analyses will include % exceedences in additional sensitive areas indicated by the model (i.e. upper Lake Wateree). Actual % exceedence targets used for testing and TMDL development should be in accordance with SCDHEC's definitions for water quality contraventions.

Subject: DePinto comments on WARMF after Feb 3 mtg.doc
From: "Joe Depinto" <jdepinto@limno.com>
Date: Wed, 5 Mar 2003 14:36:52 -0500
To: "Hank McKellar \(E-mail\)" <hmckellar@sc.edu>, "Daniel L. Tufford \(E-mail\)" <tufford@sc.edu>, <wool.tim@epa.gov>, <jdbowen@uncc.edu>
CC: <HARDENCW@COLUMB32.DHEC.STATE.SC.US>, <wilsonrl2@DHEC.SC.gov>, <STECKEMK@DHEC.SC.gov>

Hank and Dan,

This email is intended to share with you and the rest of the modeling panel some thoughts and comments I had subsequent to our February 3 meeting. Your summary minutes captured most of our discussion, but I wanted to present some specific thoughts and suggestions that I had. Please forward any update of the model calibration that you would like us to review. I am also interested in whether any additional site-specific model input data or calibration data have been obtained.

Data and Calibration

First, with regard to model calibration, I think we all agreed that the calibration, particularly between Lake Wylie and the Fishing Creek Reservoir tailrace, could be improved. While a reasonable fit seems to be present at the Lake Wylie tailrace, the model seems to under-predict the TP concentration at Fishing Creek Reservoir and both TP and chlorophyll a in Lake Wateree. There are two possible reasons for this model-data discrepancy: 1) the model is removing too much TP from the water column in the river reach between the two points; and 2) the model is under-estimating the load (probably nonpoint source loads) to the system within that river reach. Based on a review of the current model calibration, my opinion is that it is the latter. My opinion is primarily based on a belief that some P sink will occur in the system and the rate in the existing model calibration seems reasonable. Also, there are certain parameters that affect the nonpoint source loading that appear to have been assigned generic default values or at least uniform values across the watershed. I would strongly urge the modelers to investigate the feasibility of attaining a better calibration by increasing nonpoint source loads through the adjustment of the following parameters: TP in surface soils, partitioning coefficient for phosphorus in soils, fertilizer application rates, extent and width of buffer zones, and the soil erosivity coefficient. All of these parameters have a potentially strong influence on NPS phosphorus loads as well as being somewhat uncertain in their specification on a site-specific basis. In investigating these parameters relative to the model calibration, I would suggest first revisiting how each of these was initially set in the model and attempting to locate any site-specific data that might provide justification for their adjustment. Another thing to try would be to adjust these parameters as far as possible within typical literature ranges in the direction that would increase runoff phosphorus loads and observe the model output response. This is essentially determining whether increasing NPS loads within reason can account for the under-prediction. A similar bounding analysis could be done for option 1 (the in-stream sink hypothesis) by adjusting in-stream P loss processes to zero so that P is transported as a conservative substance (again, this is highly unlikely but at least bounds the problem). I would also suggest revisiting the flow calibration to investigate the extent to which the flow might have been underestimated (especially during high flow events); this could be another reason for NPS P load being too low in the model. Finally, we know that concentrations of TP typically will go up in a river under higher flow events due to erosion that results from runoff. This might be used to determine which of the above hypotheses is most likely by breaking the calibration up into base flow results (no runoff occurring) and higher flow ranges when NPS are contributing to river concentrations. If, for example, the main model-data discrepancies are in the higher flow range, then it is quite likely that NPS loads have been under-estimated. If both ranges are biased low in the model, then perhaps both factors require attention.

Even after applying this strategy for carrying out a recalibration, a decision might still be made that more data collection might be necessary to better constrain the model. I expect that given the available calibration data for this system and the number of parameters in the model that may potentially be adjusted to affect a calibration that the model is what we call under-constrained (or under-determined). We all agreed at the meeting that water quality data for model calibration was woefully lacking, especially in its ability to confirm model estimates of NPS loads. What would really help would be if additional data of two types were obtained: 1) site-specific measurements of model coefficients or input parameters that otherwise had to be specified via calibration or default literature values; and 2) additional state variable or process rate measurements that could be used to better constrain the calibration. For that former, I had already suggested some NPS load parameters that could benefit measurement in the field. The second type is, of course, something like data collection during runoff periods that represent a measurement of P runoff load from a localized sub-catchment or a small group of model segments along one of the tributaries. I suggested at the meeting that Dr. McKellar had some data from upper Fishing Creek watershed; but he indicated that they could not use it because his lab was not State certified. Jim Bowen had indicated that there might be a recent (2001) intensive survey by Duke Power in Lake Wateree that was not currently in the model database. He also thought there might be more spatially intensive data in Sugar Creek. I suggest that the PIs follow up on these potential sources of additional calibration data.

Confirmation, Uncertainty Analysis and Margin of Safety

Model confirmation is an important part of building confidence in the model for management application in the TMDL process for establishing the system assimilative capacity and for making load allocations. This is particularly important when attempting to use the model to assess areas of the system for which there are no corroborative data, such as the upper segments and some embayments of Lake Wateree. It might be problematic to apply the model in these areas if there is a high degree of uncertainty with regard to the nonpoint source loads and response to those loads in these areas.

I concur with the concept of trying to use the ?92-?93 data set as a confirmation test of the model (i.e., run model without changing coefficients, only forcing functions and comparison with field observations). This confirmation test along with judicious sensitivity analyses can be used to make an estimate of the uncertainty in model forecasts and thereby establish a margin of safety for use in conducting the TMDL allocations (see Dilks, et al. 2002 paper on MOS determination). It is possible that this analysis will produce an MOS that is unacceptably high. In that case, I would consider either conducting additional data collection to reduce uncertainty in the model calibration-confirmation or consider an Adaptive Management approach to achieving water quality targets in any number of ways. Again, LTI has developed a paper as part of our WERF project that discusses the application of an adaptive management approach especially valuable for systems in which NPS loads are a significant portion of the total load (Freedman, et al. 2002).

Model Application/TMDL Water Quality Targets

A very important decision yet to be made is the specification of water quality targets for the TMDL. This involves several issues, including specification of parameters (the group has suggested that it is important to focus on both phosphorus (0.06 mgP/L standard) and chlorophyll-a (0.04 mg/L)), specification of spatial and temporal criteria (where and when will the system response be tested (e.g., is it important to meet TP standard in winter when other factors such as temperature and light control algal growth), averaging of model output in space and time to compare with system measurements, and the allowable percent exceedences in assessing compliance. I urge the PIs to try to get a decision from DHEC on this issue before any model application runs (sensitivity analyses or example load allocations) are completed and interpreted. The important thing is the assessment of whether model output is compatible with target specification. A related issue in making this specification is the variability of P/chl ratios through the system, both in terms of observed data and model results. This indicates that factors other than TP are controlling algal growth. It is my opinion that the chlorophyll-a target should take precedence in these situations, because this is actually the response of concern when setting a TP target and the standards above are based on a regional analysis that provides an average TP/chl ratio.

Another important consideration in model application is the fact that flow variations, either by precipitation-runoff events or by hydrologic controls via dam operations can significantly affect the relative contributions of point source and nonpoint source loads and the resulting phosphorus and chlorophyll a concentrations in the river. For example, high flows resulting from wet weather events will contribute more NPS phosphorus loads to the system and, thus, be responsible for increases in TP levels. On the other hand, low flow, high temperature conditions will provide more opportunity for algal growth in lakes because of longer hydraulic retention times. Therefore, great care must be taken in selection of flow conditions that are input to the model during system TMDL calculations. This analysis will impact the decision regarding set of conditions (i.e., ?critical conditions?), such as flow, wet weather situations, temporal and spatial averaging ranges, and percent exceedence allowed, under which DHEC will evaluate compliance with water quality standards?

Finally, I would like to reiterate the types of model runs that would be useful for demonstrating model utility with regard to TMDL load allocation. In the Coalition?s letter to DHEC following the August stakeholder meeting, we made some scenario suggestions, which I will repeat below:

?Once the modeling expert panel (discussed at the July 31 Stakeholders? meeting) has concluded that the model is adequately developed for management decision application, the Coalition recommends that the following simulations be performed. The Coalition views this as an iterative process. Additional simulations will be necessary once the technically feasible nonpoint source load reduction amounts have been calculated, and DHEC has other sufficient information with which to make allocation decisions for the TMDL process.

1. Assume achievement of the point source load reductions required in existing NPDES permits, and simulate the effect on phosphorus and chlorophyll a levels of reducing overall nonpoint source loadings by 100%, 50%, and 25%.
2. If the simulation in number 1 predicts unacceptable phosphorus and/or chlorophyll a levels at any of the nonpoint source loading reduction percentages, simulate the total point source load reduction (expressed

in pounds per an appropriate time period) beyond existing NPDES limits that will be necessary for each nonpoint source loading percentage assumption.

3. Divide the Catawba River system into segments that separately contain the lakes and any river stretches deemed by DHEC to be impaired by nutrients. For each segment of the Catawba River for which the model predicts water quality standards excursions even after achievement of point source load reductions required in existing NPDES permits, simulate the effect on each segment of reducing nonpoint source phosphorus loadings by 100%, 50%, and 25%, from just the loads flowing into each respective segment from adjacent land uses.?

Also, probably one of the first demonstration scenario runs with the calibrated model should be to run the model using existing permit limits after compliance schedules are completed (e.g., Bowater) or improvements made and stricter limits are in effect (e.g., CMUD). This would provide a reference for where we might be once these pending load reductions are in place; it would give a starting point for looking at improvements attainable with nonpoint source load reductions.

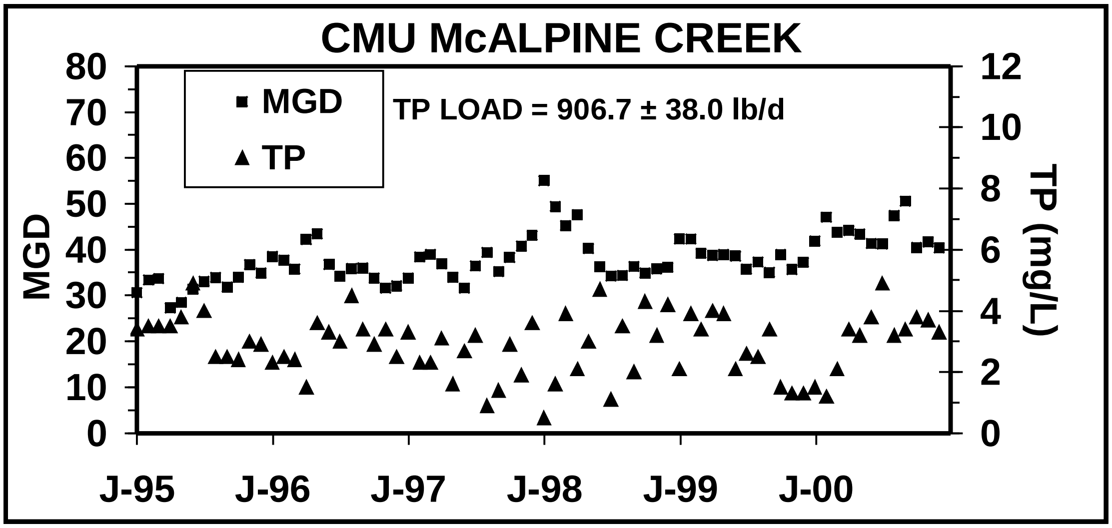
APPENDIX D

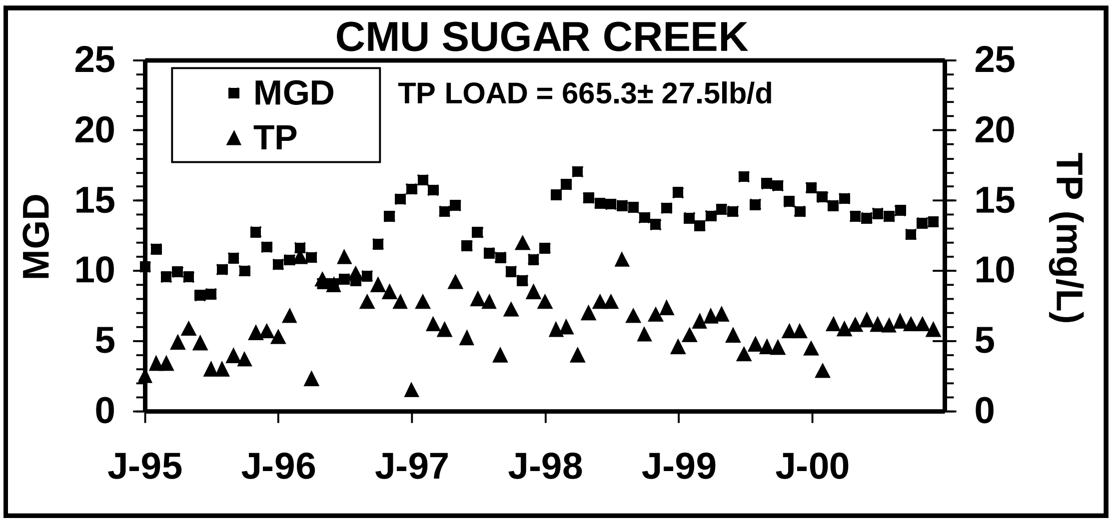
Charts of Monthly Discharge Monitoring Data for Major Point Sources in the Lower Catawba Basin

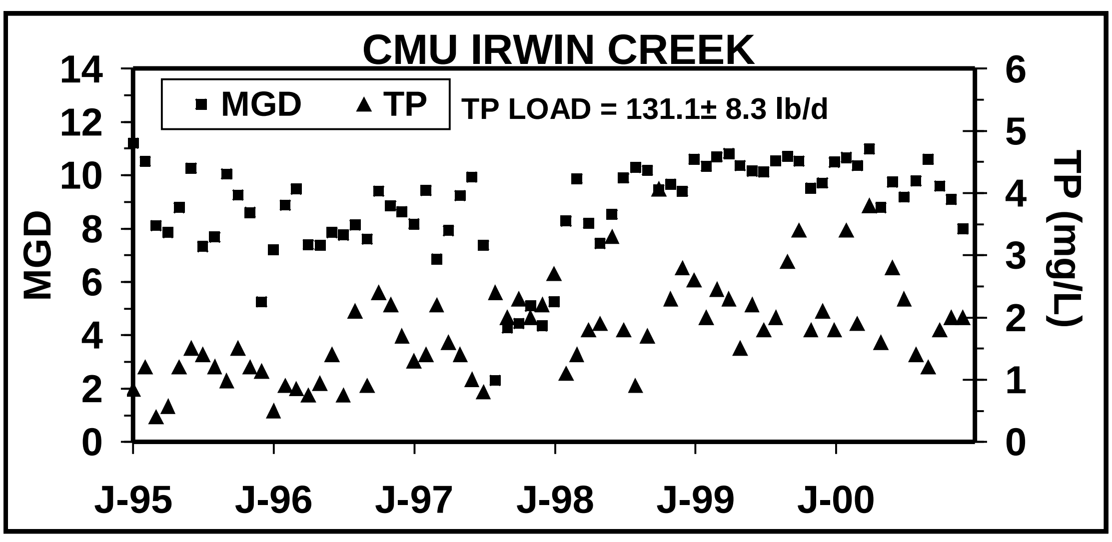
The following charts represent the detailed discharge data included in the calibrated WARMF model. Systech Engineering and USC assembled these data from monthly discharge monitoring reports and personal communications with facility engineers. These data represent discharge volumes (MGD), total phosphorus concentrations, and mean loading (lb/da) from 1995-2000. The details for City of York and Springs Industry are not included here since they represent relatively minor sources of phosphorus loading for the Lower Catawba. They are included in the model as listed in Table 2 of the main report.

LIST OF CHARTS

1. NC MUNICIPAL DISCHARGES







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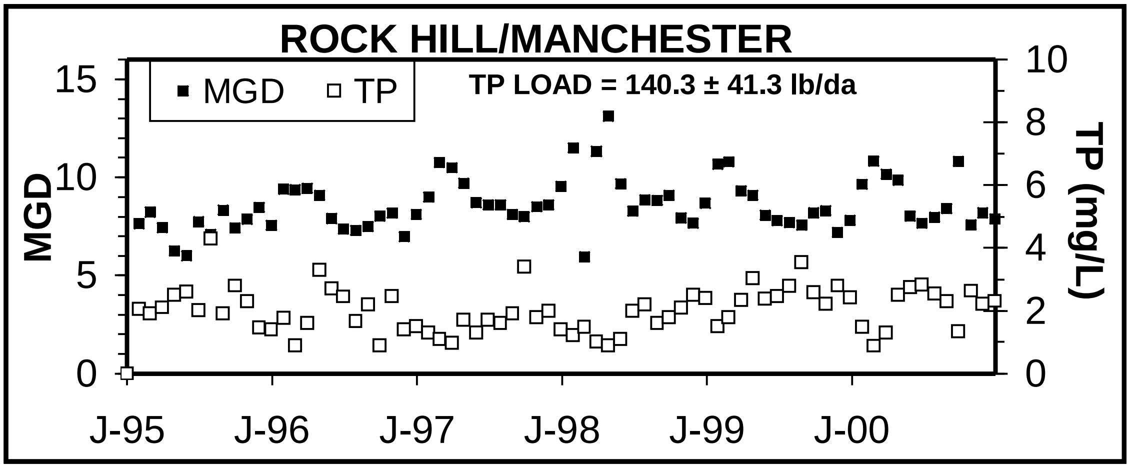

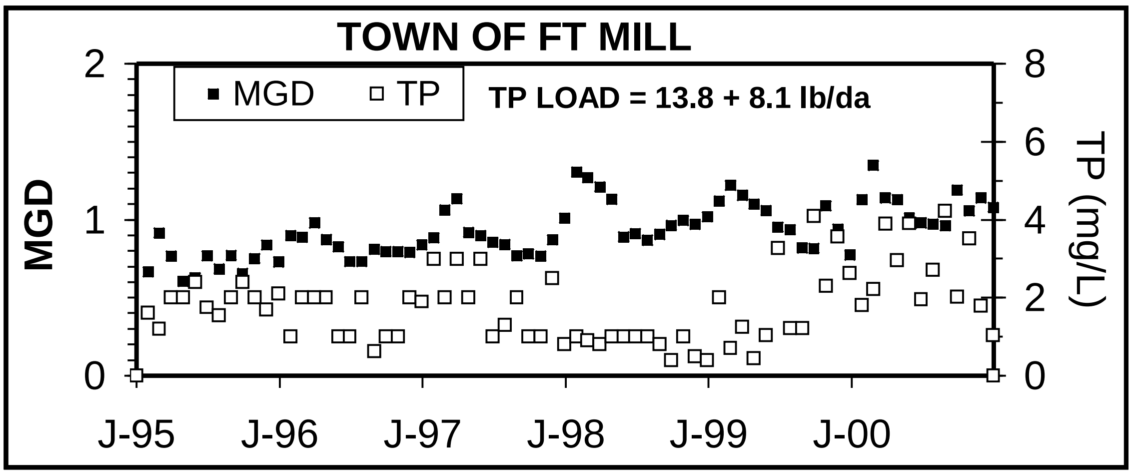

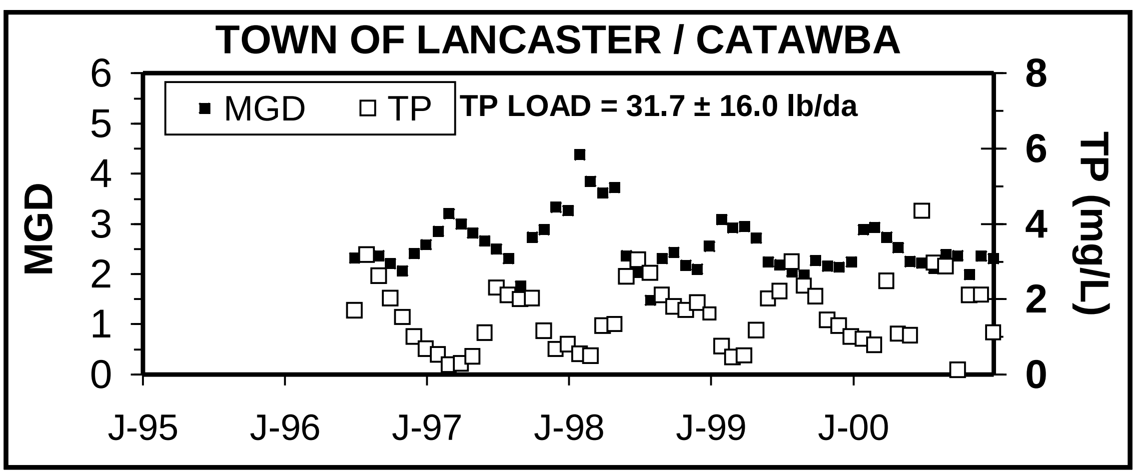

3. SC INDUSTRIAL DISCHARGES